ELEMENTS
OF
ORDNANCE

HAYES

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AND SONS

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Columbus, Ohio

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A Textbook for Use of Cadets of the United States Military Academy

PREPARED UNDER THE DIRECTION OF

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A revision of the "Textbook of Ordnance and Gunnery," by Colonel Earl McFarland, formerly Professor of Ordnance and Science of Gunnery, United States Military Academy

NEW YORK

JOHN WILEY & SONS, INC.

LONDON: CHAPMAN & HALL, LIMITED

8/42

PRINTED IN THE U. S. A.

PREFACE

The course in Ordnance and Gunnery given to Cadets of the First Class, United States Military Academy, is concerned primarily with the combat equipment of the Army. It covers service weapons and ammunition, the instruments and other accessory equipment required, the automotive combat equipment which has come to play such an important part in modern warfare, and other subjects so closely related to the design, construction, operation, or service utilization of war matériel that their consideration is necessary. The course is distinctly a professional one. The study of basic principles and fundamental theories, and of the construction, operation, and use of standard service weapons and related equipment, is supplemented by practical work in shops and laboratories.

In recent years, the weapons of attack and defense have increased greatly in number, in variety of types, and in complexity of design. The changes reflect the efforts of nations to increase the fire power, mobility, and general combat effectiveness of their armed forces through improvements in their matériel. In the fabrication of this equipment new processes, technique, and materials have been employed, and advantage has been taken of general technical and industrial progress and engineering developments.

The changes in theory and in practice, and in types and designs of matériel, have made the preparation of this book necessary. Essentially it is a revision of McFarland's excellent book "Ordnance and Gunnery," published in 1929. A considerable amount of new material has been added and many chapters have been rewritten and changed. It is not intended that this shall be an encyclopedia of ordnance; the field is too broad and the subjects comprised too numerous and comprehensive to be covered fully in a single volume. On the other hand it has not been possible to cover all the material desired; certain new processes of manufacture, developmental and experimental projects, and items of equipment necessarily have been excluded, or covered only in a broad and general manner, by reason of their confidential nature or restrictions against publication. The textbook represents, therefore, the author's selection and compilation, from available material, of subject matter which would best meet the requirements of the course of instruction,

which is designed to give to the graduating cadet a broad ordnance foundation on which he can build in the future, and on which he can base such further technical studies as may be required by his military assignments. In carrying out the Department's educational objectives, it is recognized that the book must be supplemented by lectures, demonstrations, and practical instruction in shops and laboratories.

The preparation of this textbook would not have been possible without the cooperation and assistance of the following officers of the Ordnance Department who were on duty in the Department of Ordnance and Gunnery during all or part of the period of its preparation: Major W. W. Warner, Capt. D. J. Martin, Capt. W. W. Holler, Capt. W. E. House, Capt. B. S. Mesick, Capt. E. S. Gruver, Capt. P. L. Deylitz, Capt. D. L. Van Syckle, and Capt. J. L. Holman. Without attempting to itemize the nature and extent of their services, I gratefully acknowledge the loyal support and assistance received from them.

I am especially indebted to Mr. R. H. Kent, Dr. L. S. Dederick, and Lt. Col. H. H. Zornig, of the Research Staff of Aberdeen Proving Ground, for the chapters on Exterior Ballistics, Probability of Hitting, and Bombing from Airplanes, and for the reading of proof of these sections of the book.

Valuable assistance has been given by the Office of the Chief of Ordnance, Picatinny Arsenal, Rock Island Arsenal, Frankford Arsenal, Watervliet Arsenal, and Aberdeen Proving Ground. Special acknowledgment is due Col. N. F. Ramsey, Col. A. G. Gillespie, Col. L. D. Booth, Maj. H. F. Safford, Maj. J. K. Christmas, Maj. W. R. Gerhardt, Maj. C. H. Morgan, and First Lieut. D. G. Ludlam, all of the Ordnance Department, for their cooperation and assistance. The entire manuscript for the book was typed by Miss Beatrice Lynch, to whom I extend grateful thanks. Acknowledgment is made to the Signal Officer, West Point, for photographs used in assembling the manuscript.

Various textbooks and publications were used in the preparation of this book, and it contains little that, in some form, has not been previously published. Credit is hereby given to the following: to Major General W. H. Tschappat for authority to use material from his book, "Ordnance and Gunnery"; to Colonel Earl McFarland for helpful advice and authority to use material from his book, "Ordnance and Gunnery"; to the editor of *Army Ordnance* for information and cuts for illustrations; to Lt. Col. J. L. Hatcher for authority to use illustrations from his article entitled "Automatic Firearms," which appeared in *Army Ordnance*; to Prof. Harry L. Campbell, author of the textbook, "The Working, Heat Treating, and Welding of Steel," for authority to use in the chapter on metals certain illustrations and material; to the Society of

Automotive Engineers for authority to use S. A. E. specifications; to The Chemical Foundation and Prof. J. Enrique Zanetti for authority to use material and one illustration from the book "The Significance of Nitrogen"; to the Riehle Testing Machine Division for the cut of the Brinell machine. Much information has been obtained from War Department Technical and Training Regulations, and from other official sources.

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DEPARTMENT OF ORDNANCE AND GUNNERY
UNITED STATES MILITARY ACADEMY
West Point, New York
January 6, 1938

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ELEMENTS OF ORDNANCE

CHAPTER I

PROPELLANTS AND HIGH EXPLOSIVES

1. General.—An explosive may be defined as a substance which, when subjected to heat, impact, friction, or other suitable initial impulse, undergoes a very rapid chemical transformation, forming other more stable products entirely or largely gaseous, whose combined volume is much greater than that of the original substance. Invariably a considerable quantity of heat is developed, which is sufficient not only to propagate the explosion from the initial point or area throughout the mass, but also to heat the products to a very high temperature. The pressure produced by an explosion is due to the gases evolved and is dependent on their volume and temperature. The work done by an explosive depends primarily upon the quantity of heat given off in the reaction.

The essential properties of a military explosive, or the basic conditions to be satisfied, are: (1) The reaction shall not take place until a suitable initial impulse is applied; (2) the reaction must be extremely rapid; (3) there must be complete or nearly complete conversion into gaseous products; (4) the reaction must be exothermic; (5) effected without the aid of any exterior element such as oxygen; and (6) without the aid of exterior energy, such as heat, except that necessary to initiate the action. Certain of these stipulated conditions may be met by substances not classed as explosives; however, it is this particular combination of phenomena which distinguishes an explosive and differentiates it from other substances.

Various explosives differ widely in sensitiveness, rapidity of reaction, energy content, brisance or shattering capacity, stability, and type or intensity of initial impulse required. For each military use, there are certain well-defined properties which an explosive must possess, and for each such specific use the particular explosive is selected which best meets the rigid requirements specified. Practically, the use of certain explosives of great power is precluded because of their extreme sensitivity.

Based upon their constitution, explosives may be grouped as follows:

a. Those consisting of a single definite chemical compound, such as nitroglycerin or trinitrotoluene.

b. Those which consist of two or more chemical compounds each of which is an explosive, or of one or more explosive chemical compounds and one or more non-explosive elements or compounds. Examples of this class are (1) the so-called double-base powders which contain both nitroglycerin and nitrocellulose, and which may also contain inert materials added for special purposes, and (2) dynamite, which consists of nitroglycerin absorbed in a material which may be either inert or of such character that it plays a part in the explosion.

c. Those which consist of several elements or compounds no one of which is itself an explosive, but which together form an explosive mixture. An example of this is black powder, which is a mechanical mixture of potassium nitrate, charcoal, and sulphur.

While a great many compounds and mixtures may be classed as explosives, practically only those containing oxygen and oxidizable elements such as carbon and hydrogen are used to any great extent. The oxygen is generally in combination with nitrogen, as in the radicals NO, NO_2, and NO_3, and on explosion separates therefrom and unites with the oxidizable elements. The heat given off is the difference between that required to break up the explosive into its elements and that developed on recombination of these elements, or the difference between the heats of formation of the explosive itself and of the products of explosion. Other explosives, however, of which lead azide (PbN_6) is an example, are sensitive endothermic compounds which readily break up into their elements with generation of heat and do not depend upon combined oxygen for their explosive effect.

The following represent typical explosive reactions, the left-hand member indicating the chemical formula for the explosive and the right-hand member the products of explosion:

$$2C_3H_5(NO_3)_3 = 6CO_2 + 5H_2O + 3N_2 + \tfrac{1}{2}\,O_2$$

$$2C_6H_2(NO_2)_3ONH_4 = 3CO_2 + 8CO + 6H_2 + 4N_2 + C$$

The first of these is nitroglycerin and the products are entirely gaseous. The second is ammonium picrate and, although the products are largely gaseous, carbon is included as a solid product. It may also be noted that certain of the gases which may result from explosive reactions are inflammable, for example CO, H, and CH_4, whereas others such as CO_2 and N are not.

2. Classes of Explosives.—According to their rapidity of reaction and characteristic action, explosives are classed as *low* or *progressive explosives* and *high explosives*. Although there is no sharp line of demarcation between the two classes, and within each class may be grouped explosives of rather widely varying properties, classification according to rate of decomposition and other distinctive characteristics may be made readily. Black powder, smokeless powder, and most primer mixtures are classed as low explosives, whereas the explosives employed as bursting charges in shells and bombs, and as charges in detonators and boosters, are classed as high explosives.

Based upon their principal military uses, explosives may also be classified as:

a. Propellants, which include only those low or progressive explosives whose rate of combustion is sufficiently slow to permit their use as propelling charges in guns.

b. Bursting charges, which include those explosives in which decomposition when once initiated under confinement may proceed with such extreme rapidity as to preclude their use as propelling charges, but whose violent disruptive or blast action makes them particularly suitable for use in shells, bombs, and mines, and for demolition purposes.

c. Initiators, which include those sensitive explosives or mixtures used in caps, primers, detonators, and boosters to initiate the explosion of other explosives, generally less sensitive.

3. Low Explosives; Propellants.—In low or progressive explosives, the explosion progresses from the point or surface ignited initially, by the heating of successive layers to the ignition temperature. They burn on the outside or exposed surfaces only. The explosion differs from the burning of other combustible substances, such as wood, in that combustion proceeds at a much faster rate in the explosive material, and the explosive contains within itself the oxygen required for the reaction.

The various low explosives differ considerably in their rapidity of reaction and this, with other characteristics, determines their use. Under ordinary conditions, the rate of combustion is relatively slow, but increases greatly if the explosion takes place under high pressure. For example, a grain of smokeless powder will burn in the open air at a rate of about 0.05 in. per second, but under the maximum pressure obtained in firing a cannon, about 36,000 lb. per sq. in., the rate of burning is increased to 50 or 60 in. per second. This rapid increase in rate of burning with increase in pressure permits a large charge of the same powder to be consumed in less than a quarter of a second when fired in a cannon. Not only do external conditions affect the character of the explosion, but also the physical condition of the explosive itself. For example, it

will be shown later that the density of a given powder, and the size and form of grain, affect the rate of combustion and of gas evolution.

Low explosives are not satisfactory for general use as bursting charges or shell fillers, because of their relatively slow reaction. Rupture of the projectile takes place before combustion is completed, with the result that a considerable part of the energy of the explosive would be wasted, poor fragmentation would be obtained, and the fragments would have little energy. There are, however, exceptions to this. E. C. smokeless powder is used in our standard fragmentation grenades, and black powder has been used to a certain extent in 37-mm. L. E. Shell. Although both these substances are low explosives, they are comparatively fast burning, and when finely granulated produce satisfactory fragmentation in certain types of ammunition. Such use of low explosives is exceptional.

Although all low explosives cannot be used as propelling charges in guns, all propellants are low explosives. Their relatively slow action, the progressive evolution of gas as combustion proceeds, the resulting pushing effect exerted on the base of the projectile, and the ability to control, within limits, the rates of combustion and evolution of gas, and consequently the pressure developed in the gun, satisfy the basic requirements for propellants. A high explosive could not be used for this purpose.

Ignition of propelling charges in guns is initiated by flame from a primer, which may be of the electric, percussion, or friction type. In addition to the priming mixture, all primers for cannon contain an additional charge of black powder to increase the initial flame, and to insure complete ignition of the propelling charge. Further, because of difficulties in securing complete and uniform ignition of large propelling charges, *igniters* or *igniting charges* of black powder are attached to the cartridge bags containing the propellant, or are located within the propelling charge. Black powder is efficient as an igniting agent because of its high rate of combustion; the hot gases are evolved rapidly and with sufficient pressure to envelop the propelling charge almost instantaneously.

4. High Explosives.—High explosives are those in which the reaction which has been initiated by heat or shock may proceed with extreme rapidity. The explosion which is transmitted practically instantaneously throughout the mass is termed *detonation*, or *high-order* explosion, to differentiate it from *low-order* explosions, such as the rapid combustion of propellants.

The mechanism of detonation is not definitely known although various hypotheses have been advanced to account for the phenomenon.

It is generally assumed that the energy responsible for the extremely rapid decomposition is propagated through the charge in the form of a mechanical or shock wave, somewhat similar to a sound wave. The wave may be initiated by an initial sensitive detonating agent, by heat, or by mechanical shock, which causes immediate decomposition of the first increment or layer of the charge. The energy liberated thereby reinforces the original wave, and, as this process is repeated, the wave is transmitted at high velocity throughout a charge of indefinite length. Thus, high explosives are characterized essentially by their rapidity of decomposition when once initiated and the great amount of energy released.

The speed of the explosive wave or the rate of detonation varies considerably in the various high explosives, and may vary in a given explosive under different conditions. For example, under similar conditions of confinement, trinitrotoluene (TNT) and nitroglycerin detonate at rates of 6800 and 8400 meters per second, respectively. The degree of confinement will affect these rates somewhat, but not to the same extent as in low explosives.

The term *brisance* refers to that quality or property of a high explosive evidenced by its capacity, upon detonation, to shatter any medium confining it. This property is different from that of the power or strength of an explosive; brisance is dependent upon the rapidity of the reaction, whereas explosive strength depends upon the quantity of gas evolved and the heat given off. Although the brisance of an explosive is indicated accurately by determination of its rate of detonation, practically the disruptive or shattering capacity of an explosive under investigation may be determined *relatively* by exploding it in a standard metal container such as a 75-mm. shell, in a sand-filled chamber, and comparing the resulting fragmentation with that produced by a standard explosive.

High explosives differ greatly in sensitivity, and their action may be influenced by physical conditions or by the nature of the exciting cause. Sensitivity to impact or shock produced by the application of mechanical force is a function both of the intensity of the force and of the rate at which applied. A sensitive explosive may withstand a very great load applied slowly, as in a press, but detonate violently under a suddenly applied force, such as a sharp hammer blow. The comparative sensitivity of various explosives is commonly determined by the drop test, which involves the measurement of the minimum height from which a given weight must fall in order to produce detonation of the explosive. Such tests are necessary not only to determine the sensitivity of those initiating explosives used in primers and fuzes which are to be set off by

a blow, but also to indicate the *insensitivity* of high explosives used in ammunition such as shell and bombs, to the shocks incident to handling and transportation, to firing in guns, and to impact against the target.

Many high explosives are not readily detonated by direct application of heat or by mechanical blow, but require that type of shock produced by the detonation of other more sensitive explosives. Sensitivity of an explosive to detonation is generally expressed in terms of the minimum amount of mercury fulminate required to give complete detonation consistently. Mercury fulminate is extremely sensitive and is readily detonated by heat, shock, or impact. It is commonly employed in detonators and detonating caps to initiate the explosion of the main charge. Lead azide is also used to some extent as a detonating agent. Some high explosives are so insensitive that they cannot be detonated completely by mercury fulminate or lead azide, or would require too great an amount of these agents. Accordingly, it is the normal practice in high explosive ammunition to incorporate a *booster* in the explosive train, located between the detonator and the main explosive charge. Tetryl is the standard booster explosive. Although less sensitive than the initial detonating agent, it is readily exploded by it, and its explosion is of such violence as to insure complete detonation of the still less sensitive main charge.

In designing any explosive system, such as that employed in shell and bombs, the explosive selected for each component must possess to a precise degree the particular properties of brisance, sensitivity to detonation by initiators, and insensitivity to incidental and unavoidable shock which will fit it for such use. Furthermore, each explosive element must be consonant with the others of the system to insure safety and certainty in use.

In addition to the fundamental requirements, there are other properties to be considered. A military high explosive should be stable, that is, retain its chemical and physical properties unaltered, indefinitely, under normal storage conditions. It should conform to standard methods of loading, or permit loading without undue danger or difficulty. It should not react with the metals with which it must come in contact to a degree not readily overcome by special loading methods. The explosive should be reasonably safe to manufacture, and certainty of supply at a reasonable cost should be assured.

5. Historical Sketch of the Development of Propellent Powders.—An explosive mixture similar to gunpowder and used in rockets and other pyrotechnics is said to have been employed by the Chinese in very ancient times.

The earliest record of the use of propellent powder in war dates

back to the battle of Crécy in 1346. Propellants have been commonly known for several centuries as gunpowder, a mixture of charcoal, sulphur, and potassium nitrate, the composition of which has varied little since its first use. In the sixteenth century, gunpowder or black powder was quite generally employed, the material actually being in the form of a fine powder or dust. To overcome the difficulty experienced in loading small arms from the muzzle with a powdery substance, a granular form was adopted about 1600. With the same end in view, attempts at breech loading were made but without success, as no effective gas check, which would prevent the escape of the powder gases to the rear, could be devised.

No marked improvement was made in gunpowder until 1860 when General Thomas J. Rodman, an ordnance officer of the United States Army, discovered the principle of the progressive combustion of powder. He found that the rate of combustion and consequently the pressure exerted in the gun could be controlled by compressing the finely grained powder into larger grains of greater density. The rate of combustion was found to diminish as the density of the powder increased. The increase in the size of the powder grains diminished the initial surface to be inflamed so that the new gunpowder in the form of relatively large grains of increased density evolved less gas during the early instants of combustion, and the evolution of gas continued as the projectile moved down the bore of the gun. By these means, higher muzzle velocities were obtained with lower maximum pressures. To obtain a progressively increasing surface of combustion, General Rodman proposed the perforated grain, and to assist in the convenient preparation of propellent charges, he suggested that the form of the grain be prismatic. As a result of his investigations, powder was thereafter made in grains of a size suitable for the gun, small grains being used in guns of small caliber and large grains for the larger weapons.

Notwithstanding the improvement gradually made in the quality of black powder, the standardization of its composition and manufacture, and the improved ballistics obtained through suitable granulation, it was not satisfactory as a propellant because of the bright flash at the muzzle, the erosive action of the gases, the large amount of smoke produced, the fouling of the gun, and the hygroscopicity of the powder. The next great advance was brought about by the introduction of smokeless powders.

Although nitrocellulose, which forms the basis for the manufacture of smokeless powders, and which is produced by the action of nitric acid on cotton, was discovered about 1845, it was not until 1886 that Vieille, a French chemist, introduced nitrocellulose smokeless powder. Previous

attempts to employ nitrocellulose as a propellant were unsuccessful because of its very high rate of combustion when used in its natural physical state, either loose or compressed. Vieille treated it with ether and alcohol, which acted as colloiding agents, forming a mushy paste. When rolled into a sheet, cut into small squares, and then dried, the product gave very satisfactory results. Shortly afterward, Nobel began manufacture of the first nitrocellulose-nitroglycerin or *double-base* powder. It will be noted that these products, and the so-called smokeless powders in general use today, are not completely smokeless, nor are they true powders since they are in the form of flakes, strips, cords, and cylinders.

Straight nitrocellulose powder was adopted in this country by the Navy in 1898. The first Army Ordnance experiments with smokeless powder were with nitroglycerin or double-base powder, which type was used in small arms ammunition until 1906. The Army adopted straight nitrocellulose powder for use in cannon in 1899, and for all weapons in 1906. A short cylindrical grain with seven longitudinal perforations has been employed generally, except in small arms and in certain small artillery weapons. Foreign practice has involved the use of both straight nitrocellulose and nitroglycerin powders, in the form of long cords, tubes, and strips.

By the end of the World War, it was apparent that certain improvements in standard powders were desirable. These powders gave a brilliant flash at the muzzle of the gun, which assisted the enemy in locating the position of a firing battery, and were subject to change in moisture and volatile content when exposed to the atmosphere. Such variations affect both the rate of burning of the powder and the energy per unit weight of charge, with corresponding variations of pressure and velocity in the weapon in which used. The post-war efforts have been directed toward the development of a propellant which would be smokeless, flashless, non-hygroscopic, and non-volatile. Standard powders of this general type have been evolved. They are termed FNH powders, which are completely flashless, or NH powders, if not completely or consistently flashless. Non-hygroscopicity and non-volatility depend upon the powder composition, whereas the flashless feature depends not only upon the composition, but also on the size and form of the grain, and the weapon in which used. Thus a given composition which is ballistically suited to two different weapons may be characterized as FNH powder in the one and NH powder in the other.

Concurrent with the development of improved propellants, there has been a marked improvement in the efficiency of the system employed for igniting the propelling charge. Under ideal ignition conditions all

grains of the charge would be ignited on all surfaces at the same instant, within as short a time as possible after the lanyard or trigger is pulled. Complete and uniform initial ignition insures that, as combustion proceeds, there will be a uniform rate of rise of pressure, in accordance with the laws governing the combustion of powder of the type used, instead of a variable and non-uniform rate. The trend of development in ignition systems is to provide the means whereby a large volume of hot gases will be produced and distributed throughout the charge, sufficient to raise every grain to the ignition temperature. To accomplish this, the flame from the priming composition is greatly augmented by an auxiliary charge of black powder in the primer and, when necessary, by the addition of a further igniter or igniting charge of black powder, as explained in Section 3. In an inadequate ignition system, only a portion of the propelling charge in the vicinity of the igniter may be ignited. The rapid combustion of the powder in this local area, prior to the ignition of the remainder of the charge, tends to produce extreme turbulence of the gases in the powder chamber, and results in irregular rate of pressure increase. This may produce "knocks" within the chamber, similar to the knock or detonation encountered in internal combustion engines. Such lack of uniformity of combustion results in variations in pressure and velocity, and possibly pressures which are dangerously high.

6. General Requirements for Propellants.—Propellent powder must be ballistically suitable for use in the weapon and with the projectile for which intended. That is, with proper granulation, it must be capable of producing the desired muzzle velocity, within the limit of maximum pressure prescribed for the weapon. It should be smokeless, flashless, non-hygroscopic, non-volatile, not unduly erosive, and the products of combustion should have no corrosive effect on metals. It should be capable of complete and uniform ignition. The grains should be uniform in size and shape, and tough instead of brittle.

Propellent powder must be capable of being stored for long periods without decomposition, deterioration, or any change which would result in non-uniform or impaired ballistic values. Some lots of smokeless powder have given satisfactory ballistic and chemical tests after 25 or more years' storage; others have deteriorated so rapidly that withdrawal from service was necessary after 5 years or less of life. The stability life depends not only on the materials used, and the care exercised in manufacture, but also on conditions of storage, particularly as regards temperature and humidity. Long stability life is attained by using only the purest raw materials, which are checked by chemical tests, by careful control of all details of powder manufacture, by the incorporation of ingredients that retard decomposition, and by hermetically sealing the

powder in storage. Stability tests are conducted before acceptance of any lot of powder, and thereafter so long as any part of the lot remains in service. By such tests, the probable life of the powder may be predicted and its condition known throughout its life.

The raw materials necessary to manufacture the powder must be readily available, in the quantity necessary to meet war requirements. Manufacture must be reasonably safe, and free from injurious effect upon the operatives. The product should be capable of being handled, transported, made up into charges, and stored in ordinary magazines under a wide variety of climatic conditions, all without undue hazard.

No propellant satisfies fully and completely all the above conditions. As development has proceeded, however, the quality of powder has greatly improved, and the optimum conditions and qualities have been met more fully.

7. Classes of Propellent Powders.—There are three general classes of smokeless powders, as follows: straight nitrocellulose, nitroglycerin or double base, and what is termed FNH powder, which may be single base or double base. All are formed from nitrocellulose, which is colloided or gelatinized through the action of suitable solvents or plasticizers, and forced through dies designed to give the proper grain cross-section or, if desired, passed through rolls to form sheets which subsequently may be cut into strips or flakes.

Chemically, nitrocellulose is an inorganic ester formed by the action of nitric acid on cellulose, usually cotton, which may be represented by the formula $C_{24}H_{40}O_{20}$. Formerly nitrocellulose was considered a nitro-compound, formed by the substitution of NO_2 groups from the nitric acid for the hydrogen of cellulose. It is now known to be cellulose nitrate, formed by the substitution of NO_3 radicals from the nitric acid for OH groups in cellulose. The nitration can be controlled so as to produce nitrocellulose of a specified nitrogen content. The product is not a *single definite* compound, but a mixture of products nitrated to varying degrees. The classification of the C_{24} series, with formulas expressed both as nitro-compounds and as nitrates, is as follows:

Designation	Formulas			Per Cent of N
Dodeka-nitrocellulose	$C_{24}H_{28}O_{20}(NO_2)_{12}$	or	$C_{24}H_{28}O_8\,(NO_3)_{12}$	14.14
Endeka-nitrocellulose	$C_{24}H_{29}O_{20}(NO_2)_{11}$	or	$C_{24}H_{29}O_9\,(NO_3)_{11}$	13.48
Deka-nitrocellulose	$C_{24}H_{30}O_{20}(NO_2)_{10}$	or	$C_{24}H_{30}O_{10}(NO_3)_{10}$	12.76
Ennea-nitrocellulose	$C_{24}H_{31}O_{20}(NO_2)_9$	or	$C_{24}H_{31}O_{11}(NO_3)_9$	11.97
Okto-nitrocellulose	$C_{24}H_{32}O_{20}(NO_2)_8$	or	$C_{24}H_{32}O_{12}(NO_3)_8$	11.12
and continuing down to	$C_{24}H_{36}O_{20}(NO_2)_4$	or	$C_{24}H_{36}O_{16}(NO_3)_4$	6.77

The three classes of nitrocellulose in general use are:

	Per Cent N
Guncotton	13.00 or over
Pyrocotton	12.60 ± 0.10
Pyroxylin	below 12.50

In the manufacture of straight nitrocellulose powder, the nitrocellulose used is pyrocotton containing 12.60 ± 0.1 per cent N, which is soluble in a mixture of two parts ether and one part alcohol, and produces a superior colloid. Nitrocelluloses of higher nitration are less soluble in ether-alcohol and the usual organic derivatives used as solvents, but sufficient gelatinization may be obtained to permit extrusion in the desired powder grain form. Pyroxylin has been found to have only slight application in the manufacture of propellent compositions.

In long-continued storage, all powders will deteriorate, owing to the decomposition of the nitrocellulose. It is customary, therefore, to incorporate in the powder from 0.5 per cent to 1.0 per cent of diphenylamine (C_6H_5NH, C_6H_5) as a stabilizer, its function being to combine with the oxides of nitrogen evolved which, if not neutralized, promote rapid deterioration. Diphenylamine, therefore, does not prevent the decomposition of nitrocellulose, but retards the rate of decomposition after it has commenced, and thus prolongs the life of the powder.

Straight Nitrocellulose Powders.—For many years the standard powders in our service were of the straight nitrocellulose type, and the greater part of the stock on hand is still of that type. The manufacturing process may be outlined as follows:

a. Nitration of the prepared and purified cotton, producing pyrocotton.

b. Purification of the pyro, removing free acids and lower nitrates.

c. Mixing of the pyrocotton with ether-alcohol to form a colloid.

d. Granulation of the powder by extrusion of the colloid through steel dies.

e. Solvent recovery and drying to remove the solvent.

f. Blending to secure uniformity.

Although this powder has given excellent results, it has these disadvantageous features:

(1) Production of muzzle flash in firing.

(2) Variation of moisture and volatile content in service, owing to storage and atmospheric conditions.

(3) Time required in manufacture for solvent recovery and drying.

Smokeless powders are deficient in oxygen. Muzzle flash is caused by the combustion of the unoxidized or incompletely oxidized constituents of the powder gases, such as H, CH_4, and CO, as they emerge from the muzzle of the gun and come into contact with the air. In order that this combustion may take place, the temperature of the gases must be above the flash point of the combined gas and air. It follows that if the temperature of the gases can be reduced sufficiently, such combustion will not take place and the round will be flashless. One means of reducing muzzle flash in any type of powder is to control the combustion through appropriate granulation, so that the propellant is completely consumed while the projectile is still well back in the bore. The gases thus cool themselves by doing work upon the projectile, and may be cooled below their ignition point when they emerge from the muzzle.

There are two types of granulation. One is the *degressive* form such as a cord, tube, or strip, in which the initial burning surface and rate of evolution of gas are relatively large but constantly decrease thereafter until combustion has been completed. The other type of granulation is the *progressive* form, in which initially the area of burning surface and rate of evolution of gas are smaller, but in which both increase progressively thereafter until the grain has been almost consumed. Per unit weight of charge, the degressive form produces its peak pressure earlier, and completes its combustion earlier, than the progressive form; hence use of degressive granulations tends to reduce muzzle flash. However, there are other factors to be considered in determining the best form of grain, and it will be pointed out later that the pressure developed in the gun depends both on the initial burning surface and upon the manner in which this area changes as the charge burns. In general, the best form of grain for a given gun is that which will give uniformly the desired muzzle velocity, with the least weight of charge, and pressures within the limit of maximum pressure for which the gun is designed. It may not be possible to obtain the desired muzzle velocity with a degressive form of grain and still remain within permissible pressure limits. Accordingly, absolute and complete elimination of muzzle flash through control of combustion, by selective granulation, is not usually practicable.

Reduction of the muzzle temperatures of powder gases below the flash point may also be effected through the introduction of cooling agents in the powder composition, as is done in our standard FNH powders. The agents used may be relatively inert materials that absorb the heat of explosion and thus reduce the temperature of the products of explosion, or which, although themselves of an explosive nature, evolve less heat than the other explosive ingredients of the composition, and hence produce reduction in temperature. The cooling agents gen-

erally chosen possess the power of gelatinizing nitrocellulose, and are non-volatile, so that the process of solvent recovery and drying is simplified and the time required for manufacture is reduced. In general, the materials incorporated in the powder to reduce flash also reduce hygroscopicity and improve the ballistic and chemical stability of the product. The addition of inert flash-reducing agents, however, reduces the ballistic power or potential of the powder. No difficulty has arisen in the use of FNH powder as a result of its having a lower potential than straight nitrocellulose powder, since it has been practicable to meet the ballistic requirements of the various weapons by employing granulations of the FNH powder slightly different from those used for nitrocellulose powder.

Another possible method of attack against muzzle flash involves the formulation of a powder composition which would yield only non-inflammable gases, or at least reduce greatly the percentage of such luminous gases as CO, H, and CH_4. Although little experimental work has been done in this direction, it is indicated that the problem of obtaining the ideal propellant which will be completely flashless in all weapons can be solved only through a combination of methods, that is, use of coolants, reduction in percentage of luminous gases, and degressive granulation.

Double-base Powders.—A double-base powder is one containing nitrocellulose and another principal explosive ingredient. Nitroglycerin powders are double-base powders, containing, usually, from 60 to 70 per cent nitrocellulose and from 40 to 30 per cent nitroglycerin. The original Cordite adopted for use in the British service contained 58 per cent nitroglycerin; later, this was reduced to about 30 per cent. Certain commercial double-base powders have a nitroglycerin content of 20 per cent or less. In the manufacture of nitroglycerin powders, various grades of nitrocellulose, from guncotton to pyroxylin, are used. The manufacture is concerned chiefly with the incorporation of the nitrocellulose and the nitroglycerin. Since only the lower nitrated products are soluble in nitroglycerin, acetone is added as a solvent for guncotton in forming the colloid.

Nitroglycerin powders have a greater potential than the single-base nitrocellulose type, and a smaller weight of charge may be used to attain a specified muzzle velocity. They are also less hygroscopic. These advantages have led to their retention as the standard military propellant by certain countries and to their considerable use in sporting ammunition in this country.

The temperature of explosion of nitroglycerin powder increases with the percentage of nitroglycerin employed and is usually considerably higher than that of straight nitrocellulose powder. Accordingly, the

gases are highly erosive in the bore, reducing the serviceable length of life of the weapon. Likewise, because of the high potential of nitroglycerin, and the greater amount of heat evolved by nitroglycerin powders, it is not practicable to add sufficient inert material to cool the gases sufficiently to produce flashlessness. For these reasons, increase in erosion and inability to eliminate muzzle flash, nitroglycerin powder is not employed in our service as a standard propellant. Other objections to the adoption of nitroglycerin powders as standard are the probable difficulty of securing an adequate supply of glycerin in time of emergency, and the added hazards incident to the manufacture of such a powder. Smaller percentages of nitroglycerin, however, are used in certain FNH powders, reducing hygroscopicity without increasing the energy content of the mixture to such a point that it is impracticable to obtain flashlessness by the addition of cooling agents.

FNH Powders.—This type of propellant is a mixture of nitrocellulose and other materials added for the purpose of cooling the products of combustion and reducing the hygroscopicity of the nitrocellulose. The following composition, when properly granulated, would provide a suitable FNH powder for certain of the smaller artillery weapons:

Nitrocellulose (12.6% N)	74%
Nitrocellulose (13.25% N)	20%
Dinitrotoluene	5%
Diphenylamine (stabilizer)	1%

Since the dinitrotoluene upon combustion liberates considerably less heat than the same weight of nitrocellulose, this powder is considerably cooler and can be granulated so that the gases at the muzzle will be below the flash point. An analysis of the gaseous products obtained by combustion of the powder in a closed chamber shows that, although the quantity of heat evolved per kilogram is considerably less than in straight nitrocellulose powder, the volume of gases produced is greater.

An example of FNH powder in which nitroglycerin is used is:

Nitrocellulose (12.6% N)	49%
Nitroglycerin	20%
Trinitrotoluene	20%
Hydrocellulose	10%
Diphenylamine	1%

Since the TNT has about the same energy content as the nitrocellulose, it was necessary to add 10 per cent of inert hydrocellulose to compensate

for the high energy content of the nitroglycerin and in order to cool the gaseous products sufficiently to eliminate muzzle flash. It is not always practicable to use the large amounts of cooling agents necessary, owing to the smoke effects produced by these inert materials.

The standard FNH powders utilized in our service are manufactured substantially according to the same procedure employed for straight nitrocellulose powder. The usual ether-alcohol solvent is used to effect gelatinization, but when materials such as nitroglycerin, trinitrotoluene, or dinitrotoluene are present, all of which have some gelatinizing action on nitrocellulose, a lesser amount of ether-alcohol is required to permit extrusion of the mixture in the multi-perforated grain form. Even without the use of the ether-alcohol solvent, it is possible by use of non-volatile plasticizers, such as named above, to obtain sufficient plasticity of the nitrocellulose to permit granulation in strip form, by first passing through rolls to form sheets and then cutting in strips of proper size. The elimination of the special equipment required for the manufacture of extruded powder and the advantage of being able to use a powder as soon as manufactured without the necessity for solvent recovery and drying might be of great importance in time of war.

FNH powder of a composition which may be flashless in one weapon may not be completely or consistently flashless in another, even with the most favorable granulation possible. This is due to the different characteristics of the two systems, including weight of charge, length of powder chamber, weight of projectile, and length of bore or projectile travel. An obvious remedy would be to employ a greater amount of the coolant in the composition, and this is practicable within certain limits. However, if used to excess, an objectionable amount of smoke is produced and the potential of the powder may be reduced to a point where a weight of charge sufficient to give the specified velocity to the projectile cannot be inserted in the chamber of the weapon. As a result of inability to eliminate flash without producing excessive smoke or compromising essential ballistic characteristics, certain weapons in our service, as for example the 155-mm. gun, employ a powder characterized as NH, of precisely the same composition as the FNH powder which is standard for all 75-mm. guns in our service.

Special Compositions.—There are other standard powder compositions, for particular weapons or for special use, which cannot be classified as belonging to any of the three types discussed above. The standard propellant for small arms ammunition consists essentially of nitrocellulose of high nitration, with a small percentage of metal incorporated which is designed to reduce muzzle flash and to eliminate metal fouling, and with the outer surface of the grains coated with a material which acts

both as a water-proofing agent and as a deterrent which slows the initial rate of burning. Although granulated in a degressive form with constantly decreasing area of burning surface, the effect of a progressive-burning type is obtained in that, after the slow-burning coating is consumed, the nitrocellulose burns with greater rapidity.

E. C. smokeless powder used in loading blank small arms cartridges, and as the explosive filler in fragmentation grenades, consists of

Nitrocellulose	80.4%
Barium nitrate	8.0%
Potassium nitrate	8.0%
Starch	3.0%
Diphenylamine	0.6%

THE MANUFACTURE OF SMOKELESS POWDER

In the manufacture of propellent powder, there are two distinct processes.

a. The manufacture of nitrocellulose of the desired degree of nitration.

b. The manufacture of smokeless powder from the nitrocellulose.

Propellants are low explosives which have a relatively slow rate of burning. If a high explosive were used as a propellant, its detonation would shatter the weapon, whereas the action of a propellant can be controlled so as to produce a pushing effect upon the projectile without danger to the weapon. The nitrocellulose used in the manufacture of smokeless powder differs only slightly in nitrogen content from that of the guncotton used as a high explosive. Materials such as nitroglycerin and trinitrotoluene used in double-base and FNH powders are themselves high explosives. There is a definite distinction between high and low explosives, but it is apparent that a material which is in reality a high explosive may be incorporated safely in a low explosive or propellent powder and desirable characteristics attained thereby.

When nitrocellulose is converted into smokeless powder, under the action of solvents or plasticizers, its physical characteristics are changed and it is transformed into a dense, tough, hornlike substance. This physical (not chemical) change transforms the material from a high explosive into a low explosive and permits its use as a comparatively slow-burning propellant rather than as a detonating high explosive. The second step in the manufacture of smokeless powder is concerned with this change of nitrocellulose into powder of the desired form and size whereby its rate of burning is controlled.

There follows a brief description of the manufacture of straight nitrocellulose powder, prepared from pyrocotton containing from 12.5 to 12.7 per cent of nitrogen.

8. Preparation of the Raw Cotton.—Cotton linters and hull fibers are the forms of cellulose most frequently used for the manufacture of nitrocellulose, although other grades of cotton and sometimes wood pulp are employed. Cotton linters and hull fibers are used not only because of their cheapness and availability but also because, being shorter, they are more readily and completely nitrated.

Purification.—Raw cotton contains an appreciable quantity of vegetable oils and resinous material which must be removed prior to nitration. A charge of the raw cotton is heated under pressure, in closed vats, with a weak caustic soda solution. After this digesting treatment, the cotton is drawn off into tanks, the spent caustic liquor allowed to drain, and the cotton washed until it is practically free from alkali. The treatment of the cotton thus far is usually carried out at a cotton purifying plant; the material, in this condition, is baled and forwarded to the nitrating plant.

Picking.—In order to obtain uniform nitration of the cotton, the tightly baled material must be reduced to a uniform fluffy condition, free from lumps. This operation is known as "picking" and is accomplished by passing the cotton through a machine provided with a toothed roller which carries the material into such a position that it is torn apart by rows of sharp teeth set in a revolving cylinder.

Cotton Drying.—The picked cotton is blown to the dry house where the moisture content is reduced to approximately 0.5 per cent. The drying may be carried out by placing the cotton in a large tightly closed chamber and gradually heating by hot air to a final temperature of 100° C. This process usually requires about 24 hours. A more modern and quicker method involves conveying the cotton on a continuous belt through a chamber already heated to a temperature of 100° C.

After drying, the cotton is weighed out in charges of desired size and transferred to the nitrator house in airtight containers.

9. Nitration of the Cotton.—The nitrating acid employed is a mixture, the composition of which varies according to the process employed, as follows:

HNO_3	21% to 26%
H_2SO_4	64% to 60%
H_2O	15% to 14%

The main purpose of the sulphuric acid is to combine with the water formed by the nitration reaction, and thus to prevent dilution of the

nitric acid. The spent acid recovered from the nitrators is built up to the above composition for subsequent use by the addition of fortifying acid,

HNO_3	52%
H_2SO_4	47%
H_2O	3%

which makes up the deficiency in nitric acid and a part of that of the sulphuric acid. The remainder of the deficiency is made up by the addition of fuming sulphuric acid.

Several systems of nitration are in use, the foremost processes being essentially the same in principle but varying in the proportion of nitric acid, sulphuric acid, and water used. The du Pont mechanical dipper process is by far the most satisfactory from the operating standpoint, as the loss of acid is less than in any of the other processes. This system is in most general use in the United States.

Nitration by du Pont Mechanical Dipper Process.—A nitrating unit consists of four nitrators discharging into the same centrifugal wringer, as shown in Fig. 1. Each nitrator is equipped with two vertical paddles rotating in opposite directions. The motion thus imparted to the acid tends to draw the cotton quickly beneath the surface. A charge of mixed acid, previously heated to a definite temperature, is run into each nitrator, the paddles are set in motion, and the cotton charges are added. A nitrocellulose of approximately 12.6 per cent nitrogen is produced. The entire cycle of operation requires not more than 35 minutes.

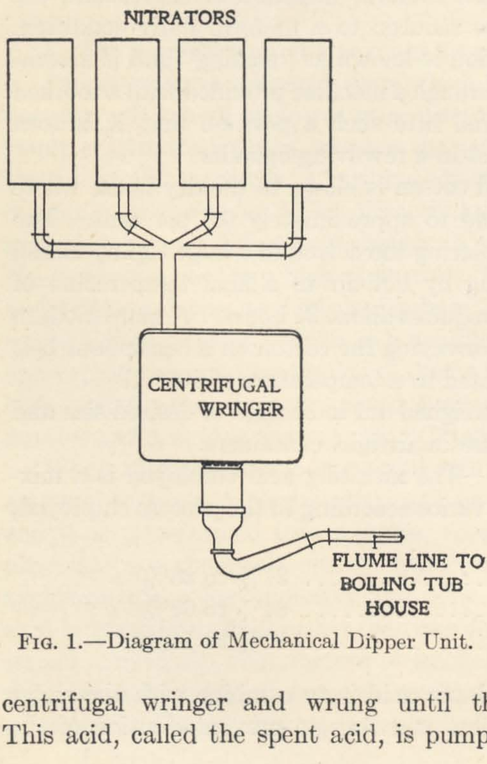

FIG. 1.—Diagram of Mechanical Dipper Unit.

Wringing.—After nitration is complete, the charges are lowered to the centrifugal wringer and wrung until the excess acid is removed. This acid, called the spent acid, is pumped to the spent-acid storage.

The nitrocellulose is forked through the bottom of the wringer into an immersion basin where it is covered with water. The material is then pumped through a flume to the boiling tub house.

10. Purification of the Nitrocellulose.—The nitrocellulose, as it comes from the nitrators, contains an appreciable percentage of acid and some fiber particles of a lower degree of nitration than desired. These undesirable impurities are removed by subsequent boiling and purification.

Preliminary Boiling.—The preliminary boiling process is carried out in large wooden tubs, as shown in Fig. 2. The charge of nitrocellulose from the nitrators rests on a false bottom in the tub and is covered by a perforated top. A square wooden duct rests on the false bottom and extends to the top of the tub. The duct serves as a heating chamber for the water, which flows from the top of the duct over the perforated top plate and is thus distributed through the charge of nitrocellulose. The nitrocellulose during this treatment is not subjected to the direct action of live steam.

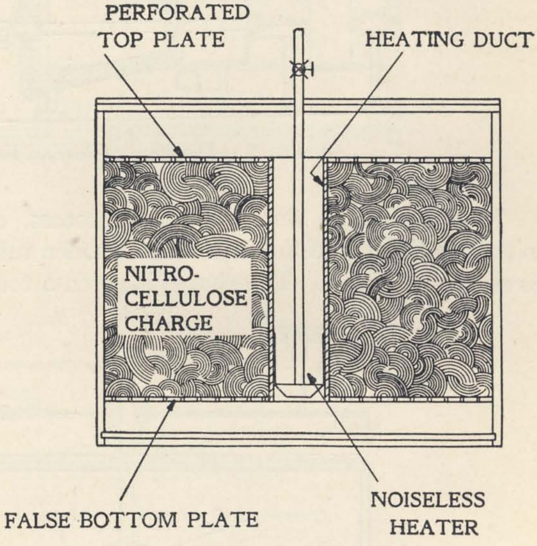

FIG. 2.—Diagram of Boiling Tub.

This hydrolyzing treatment must be of at least 16 hours' duration, according to present specifications. The total time of preliminary boiling is specified as 40 hours with not less than four changes of water.

Pulping.—The preliminary boiling operation removes the undesirable lower nitrates and the acid on the surface of the nitrocellulose fibers. An appreciable quantity of acid, however, is mechanically occluded within the fibers, and it is necessary to pulp the material to a finely divided condition before this acid can be released and removed. This is accomplished by running the nitrocellulose, with a large excess of water, through a beating apparatus. The type of beater in most general use for the manufacture of smokeless powder is the Jordan Engine, as shown in Fig. 3. This machine consists of a series of broad-bladed

knives, set in a conical rotor, by means of which the fibers of nitrocellulose are cut to very short lengths. The nitrocellulose circulates from a tank through the beating engine until it has been reduced to the desired degree of fineness.

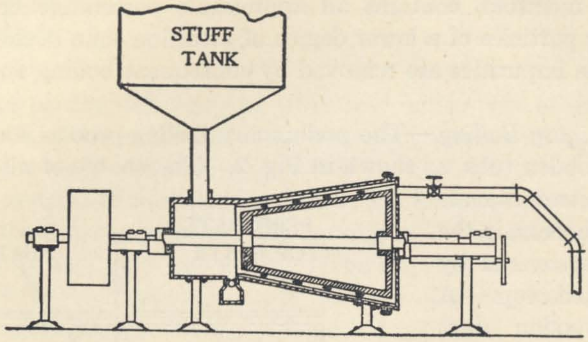

FIG. 3.—Diagram of Jordan Engine.

Poaching.—The final purifying process, called poaching, consists in boiling the nitrocellulose in large wooden tubs equipped with paddles, as shown in Fig. 4. The charge is given a total poaching treatment of

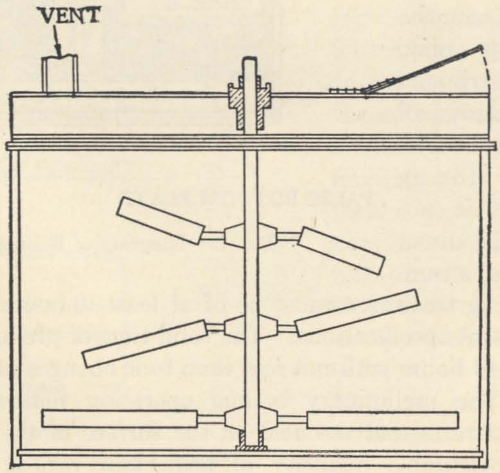

FIG. 4.—Diagram of Poaching Tub.

12 hours, with six changes of water during boiling; and then ten cold-water washings.

Screening.—The nitrocellulose from the poaching tubs is run over the packer pulp screen to remove any material that has not been thor-

oughly pulped. The packer pulp screen, illustrated in Fig. 5, consists of a plate through which slits 0.01 in. in width have been cut. The nitrocellulose is pulled through these slits by suction and any unpulped material is returned to the beaters for additional treatment.

The pulped material is then run into the blending tubs where it is blended and stored under water until needed.

Wringing.—The blended nitrocellulose is then run into centrifugal wringers where the excess moisture is removed. The material retains

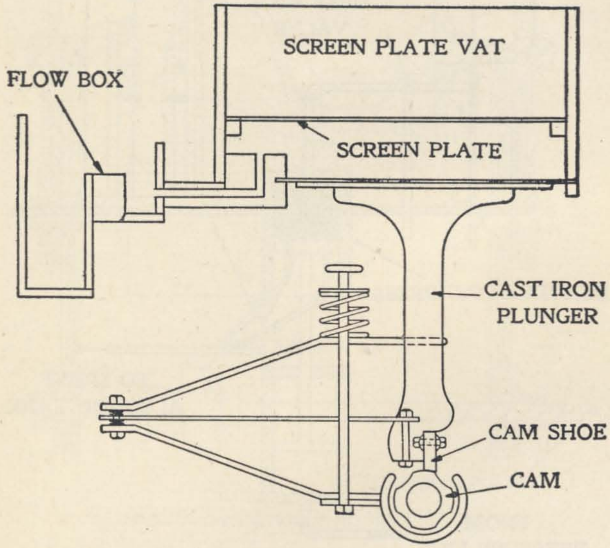

FIG. 5.—Diagram of Packer Pulp Screen.

about 30 per cent of water and is now ready for the subsequent operations of powder manufacture.

This completes the first step in the manufacture of nitrocellulose powder; that is, the manufacture of the nitrocellulose itself. A second distinct process is required to change the nitrocellulose into smokeless powder of the desired grain form.

11. Dehydration.—The nitrocellulose from the wringers is weighed out in charges of suitable size and placed in the dehydrating press, as shown in Fig. 6. The nitrocellulose is given a preliminary pressing to form the material into a block. Alcohol is now run in above the block and the hydraulic pressure again applied. The piston forces the alcohol through the block and displaces the water. Pressing is continued until the desired amount of alcohol remains in the block. The purpose of the

dehydration operation is two-fold: first, the water is removed from the nitrocellulose; second, the required amount of alcohol is introduced.

The customary ratio of solvent to nitrocellulose is 1 : 1; that is, for every pound of dry nitrocellulose, one pound of solvent is used. The solvent consists of a mixture of two parts of ether and one part of alcohol.

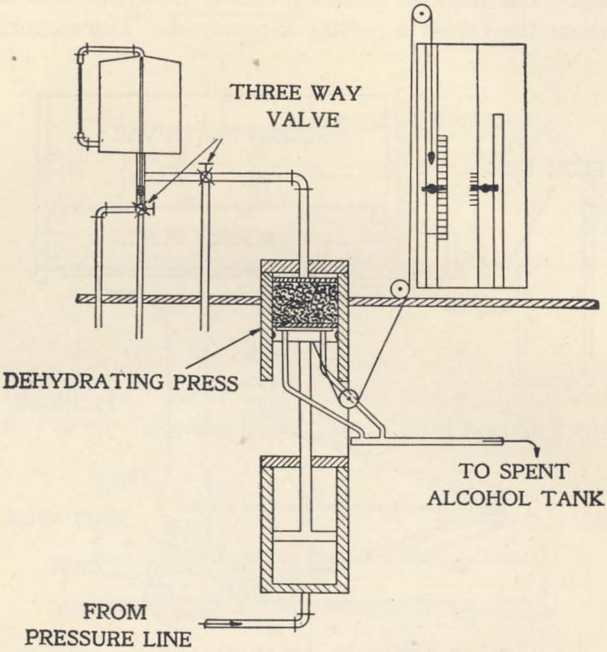

FIG. 6.—Schematic Sketch of Dehydrating System.

Therefore, in the dehydration operation, there is left in the block one-third of a pound of alcohol for every pound of dry nitrocellulose.

Block Breaking.—The nitrocellulose, containing its correct amount of alcohol, comes from the dehydrating press in the form of a friable block. In order that the material may be more readily mixed with the solvent in the next operation, it is necessary that the block be broken up. This is effected in the block breaker, a rotating drum made of heavy screening equipped with sharp prongs on its interior. The block is broken by tumbling until the material is sufficiently fine to pass through the screen of a specified mesh.

Mixing.—The powder mixer, illustrated in Fig. 7, is the machine used to obtain a thorough mixing of the broken-up block of nitrocellulose, the alcohol, and the ether. The machine consists of a water-jacketed

tank, in which the material is placed. Running in this tank are two blades rotating in opposite directions. Every effort is made to prevent solvent losses.

The broken-up nitrocellulose already contains the proper amount of alcohol. Ether (the other ingredient of the solvent) and diphenylamine (the stabilizer), dissolved in ether, are then added to the mixer.

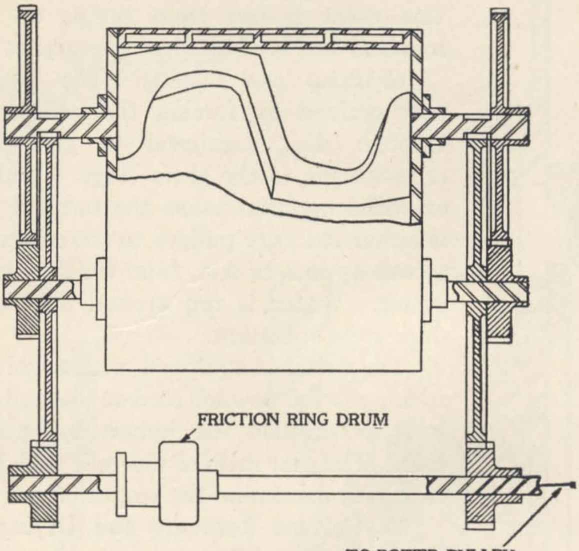

FIG. 7.—Diagram of Powder Mixer.

12. Preliminary Blocking.—The nitrocellulose, carrying its solvent, comes from the mixer little changed in appearance. Slight colloiding action takes place in the mixer. The first step in colloiding is preliminary blocking. During this process the material from the mixer is charged into a hydraulic press and subjected to a pressure of approximately 3500 lb. per sq. in.; the press is represented in Fig. 8. The resulting block is entirely different in appearance from the material as it comes from the mixer. It has been changed from a crumbly mass to a dense, translucent, brown, colloided substance. The colloiding, however, is not complete.

Macaroni Pressing.—The preliminary block is charged into the macaroni press from which it is extruded through a series of finely perforated plates. This operation removes any solid foreign matter that may remain in the powder and aids the colloiding action of the solvent by further mixing and kneading.

Final Blocking.—The material comes from the preceding step in strands having the appearance of macaroni. The strands are allowed to fall through a closed chute into the final blocking press. The operation here is similar to the preliminary blocking, except that the pressure is held on the block for several minutes. This operation completes the colloiding of the nitrocellulose, and the block at this point is free from lumps of uncolloided material and is of uniform appearance.

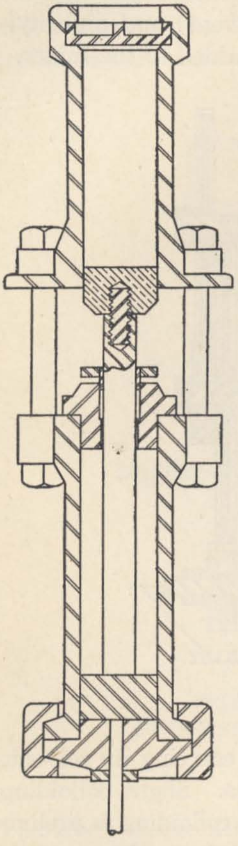

FIG. 8.—Diagram of Powder Blocking Press.

Graining and Cutting.—The final block is now grained by forcing the colloided material through dies, fashioned to give the proper cross-section to the grain (Figs. 9 and 10). The extruded material takes the form of a cord and is either led over pulleys to the cutter or allowed to coil up in a basket, from which it is fed to the cutter. Water is run around the die to cool it during the operation.

The cutter is equipped with revolving knives which cut the powder cord to desired lengths as it is fed against the knives by means of feed rolls. The gear ratio of the rolls and the number of knives determine the length of cut.

13. Solvent Recovery and Drying.—An important economic consideration in the manufacture of smokeless powder is the recovery of the ether and alcohol remaining in the green or fresh powder. This operation is known as *solvent recovery*. The principle is the same in each of a number of methods: warm air is circulated through the powder and picks up the solvent vapors; and this vapor-laden air is then forced over cold coils, whereupon the vapor is condensed and recovered. The temperature and duration of the solvent recovery operation vary according to the operating conditions.

Drying.—The solvent recovery operation is continued until the remaining solvent is reduced to 12 or 15 per cent, at which point the recovery is no longer economical. The powder is then taken to the dry house where the solvent is reduced to the final percentage required. Two methods of drying are in use: air drying and water drying.

Air drying is probably more satisfactory, considering only the quality of the finished product, but the process is very time-consuming in

operation. The powder must not be subjected to a high temperature during the first stages because excessive and uneven shrinkage will result.

Air driers are of two types: tray driers and bin driers. In the *tray driers,* the powder is placed in trays having screen bottoms and the air in the room is heated to remove the solvent from the powder. The *bin driers* operate on the same principle, except that the powder is handled in larger bulk and in narrow bins. No free circulation of air is provided

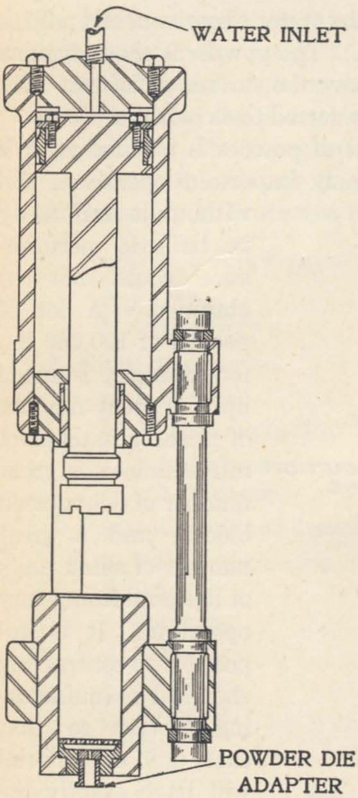

FIG. 9.—Diagram of Finishing Press.

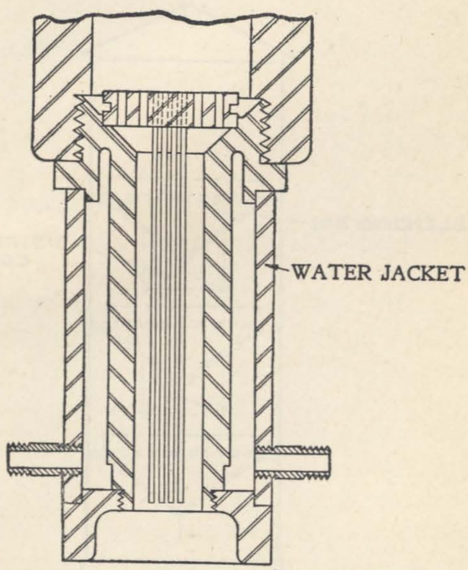

FIG. 10.—Diagram of Powder Die.

for either method, but the dry houses are opened at intervals to remove the vapor-laden air. The time of drying depends upon the size of the powder, varying from 30 days for powder of small grain, to more than 100 days for powder of the largest granulation.

Water drying is quicker. Most of the solvent is alcohol, and water has a great affinity for this substance. In the water-drying process, the water surrounding the grains absorbs the alcohol near the grain surface

and the voids created are filled by more alcohol from the inside of the grain. The process continues in this way until most of the volatiles have been removed from the powder.

The marked advantage of the *water-drying* process is that drying is accomplished in from 4 to 8 days; but it has the disadvantage that, of the total remaining volatiles, a greater percentage is moisture, and this condition decreases the stability life of the powder. The powder from *solvent recovery* is placed in tanks, and water is circulated at temperatures increasing from 25° to 55° C. The water absorbs nearly all the solvent that has remained in the powder. The powder is then given an air drying of from 24 to 48 hours to remove the surface moisture. The solvent and moisture then remaining are referred to as *volatiles.*

14. Blending and Packing.—Each lot of powder is blended after it has been dried. Blending is an extremely important operation, and without it uniformity in ballistic performance could not be obtained. A lot of powder of 100,000 lb., for example, is made up of a great number of nitrator batches of nitrocellulose, a great number of dehydrated blocks, and a great number of small units of material from every operation. It is impossible to control any chemical manufacturing process so that each unit of material will have exactly the same properties. Because of this condition, it is necessary to mix thoroughly each lot of powder to insure uniform ballistic properties.

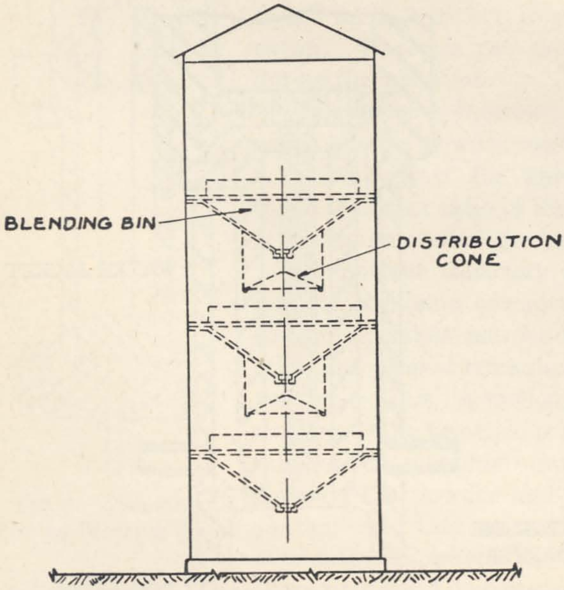

FIG. 11.—Schematic Sketch of Cannon Powder Blender.

The blending operation consists in passing the powder through conical bins until it is thoroughly mixed. The type of blender in use at Picatinny Arsenal is illustrated in Fig. 11. It consists of a vertical series of three conical bins. The powder is hoisted by elevator to fill the top bin. It is then released, by remote control, to fall over a distribu-

tion cone into the second bin and, when this is filled, is dropped similarly over another distribution cone into the bottom bin. In some instances, the blending process is repeated in order to insure a high degree of uniformity of the powder. Experience has demonstrated, however, that, no matter how long continued, blending will not produce uniformity of ballistic performance if marked irregularities in the grains exist, as, for example, if grain dimensions are abnormally variable as a result of abnormality in manufacture.

The blending operation is somewhat hazardous because of the development of static electricity, and every precaution is taken to remove static from all parts of the system.

After blending, the powder is packed in zinc-lined boxes sealed with rubber gaskets. The boxes are made airtight to insure that the powder will not change in moisture or solvent content during storage.

15. Summary of Processes in Manufacture of Smokeless Powder.—

1. Preparation of raw cotton
   a. Picking
   b. Cotton drying
2. Nitration of cotton
   a. Acids used
   b. du Pont mechanical dipper process
      1. Nitrators
      2. Wringers
3. Purification of the nitrocellulose
   a. Preliminary boiling
   b. Pulping
   c. Poaching
   d. Screening
   e. Blending
   f. Wringing
4. Dehydration
5. Block breaking
6. Mixing
7. Preliminary blocking
8. Macaroni pressing
9. Final blocking
10. Graining and cutting
11. Solvent recovery
12. Drying
    a. Water drying
    b. Air drying
13. Blending and packing

16. Manufacture of FNH powders.—The manufacture of FNH powders may be carried out substantially according to the same procedure employed for nitrocellulose powder. The usual ether-alcohol mixture is used to effect gelatinization; but when materials such as nitroglycerin, dinitrotoluene, and trinitrotoluene are employed in the powder composition, all of which have some gelatinizing effect, a lesser amount of ether-alcohol is required. Except for this difference, the mixing, pressing, graining and cutting, solvent recovery, and drying processes follow closely those employed for straight nitrocellulose powder.

TESTS OF PROPELLANTS

17. General.—At each stage during the manufacture of propellent powder, chemical tests are made to insure that the raw materials used comply fully with the detailed specifications. Standard methods of analysis are followed. Likewise, the nitrocellulose to be used, whether purchased or manufactured by the government, is tested chemically to check its composition and uniformity, and is subjected to certain standard stability tests.

The finished powder is then subjected to chemical, physical, ballistic, and stability tests prior to acceptance of the lot. Stability tests are continued so long as any of an accepted lot remains in service.

18. Determination of Moisture and Volatiles.—It has been found by experience that each size of granulation will retain a certain definite percentage of moisture and volatiles with less change than any higher or lower percentage. Since any variation in the powder in service, that is, loss of volatiles or absorption of moisture, will always result in ballistic variations, it is customary to specify the optimum moisture and volatile content for each powder composition and particular granulation. This is greater for large granulations than for small. For example, the percentages specified for the pyro powder used in the 12-in. and the 3-in. guns are, approximately, 6.5 per cent and 3.5 per cent, respectively. Much smaller percentages are specified in FNH and NH compositions.

During the drying process, tests are made to determine the residual moisture and volatile content, and when the desired percentage is reached the powder is removed from the drying house.

19. Measurement of Grains; Physical Test.—In order to obtain the desired ballistic results, a particular granulation of powder is required for each gun. It was noted that shrinkage occurs in the grain during the process of drying after granulation. To determine whether the right size of granulation is obtained after drying, careful measurements are made on 30 grains selected at random from the lot under consideration. It

will be shown later that the most important dimension of a grain is the least burning thickness or the web. The mean of the measurements of this dimension, within an allowed tolerance, must be the web thickness prescribed for the powder. In addition, the variation of individual measurements from the mean must not be great; that is, the grains must be uniform in size.

Compression Test.—When a gun is fired, the powder grains before being completely consumed are subjected to the enormous pressure of the powder gases in the gun. In addition, the grains may be thrown violently against the walls of the gun or base of the projectile. If the grains are brittle they may be broken into pieces and thus expose a larger surface of powder for burning. This increased burning surface will cause a more rapid evolution of gas and therefore higher pressures in the gun. Since it is not probable that the same number of grains would break at each round, irregular and possibly dangerous pressures might be obtained.

To insure that the grains have sufficient strength to withstand the pressure and blows to which they are subjected, a compressive test is prescribed. A number of grains are prepared by cutting off the ends so that they form cylinders, the lengths of which are equal to the diameters. Each of these cylinders is then slowly compressed endwise between parallel surfaces until a crack appears on the cylindrical surface. The amount of compression when the crack appears must not be less than 35 per cent of the original length of the cylinder.

20. Stability Tests.—*KI-Starch Paper Test.*—This test is applied to the finished nitrocellulose during the manufacture of powder. The sample, after being properly prepared and dried, is heated to 65.5° C., in a glass tube in which is inserted a piece of paper impregnated with potassium iodide and starch.

The stability of the nitrocellulose is measured by the length of time required for the products of decomposition to discolor the test paper. The specification requires that the paper shall not be discolored in less than 35 minutes. A low test usually indicates that the free acid originally in the nitrocellulose has not been removed sufficiently to give proper stability to the material.

134.5° C. Heat Test.—This heat test is utilized as an acceptance test for both nitrocellulose and finished smokeless powder, and to detect deterioration of powder in service. The sample is placed with methyl violet test paper in a test tube closed by a perforated cork stopper, and maintained at a constant temperature of 134.5° $\pm$ 0.5° C. The time period is noted when the test paper changes to a pink color, when the production of red NO_2 fumes begins, and when explosion takes place.

The minimum permissible periods at which the changes may occur are specified. For propellants, explosion must not occur within 5 hours.

120° C. Heat Test.—This heat test is at times employed in place of the 134.5° C. heat test, for double-base powders. The procedure followed is the same as in the former test, but the specified time periods are changed.

Surveillance Test at 65.5° C.—This is an accelerated storage test of master samples of each lot of powder in service, conducted at Picatinny Arsenal. Similar tests of each lot on hand may be conducted at each ordnance depot where powder is stored, because of the great variations in climatic and storage conditions; this is not standard practice at the present time.

The test consists of placing a 45-gram sample of powder in a closed bottle, maintaining it at a constant temperature of 65.5° C., and observing it daily to determine the number of days required for the evolution of red NO_2 fumes. Tests are conducted normally at intervals of one year, but when impaired stability is indicated they are conducted more frequently.

Observation Test.—This test is intended to detect the initial decomposition of smokeless powder. It is conducted at all depots and posts where powder is stored. A 6-oz. sample of each lot of powder in the magazine with a strip of methyl violet test paper is placed in a glass-stoppered bottle. The test is carried out in the magazine in which the powder or charges under test are stored. Bleaching of the test paper is taken as an indication that the powder has started to deteriorate. The test is run continuously and new samples are selected each year. Test papers which lose color gradually may remain in the bottle until they are completely bleached, but papers which show a marked change of color are replaced every two months. Report is made of any evidence of deterioration, and special stability tests are run on the lot in question, at the appropriate ordnance establishment.

21. Ballistic Test.—This is the final test before the acceptance of a lot of powder. A charge is established by firing a series of rounds, starting with a low weight of charge and gradually increasing the weight until a muzzle velocity equal to, or slightly greater than, the prescribed value is obtained or until the maximum allowable pressure for the weapon is reached. The standard powder for the particular weapon is fired at the same time, and velocities and pressures are corrected for gun erosion. Pressures and muzzle velocities obtained with the new powder are plotted as functions of the weight of charge; and the charge required to give the prescribed muzzle velocity is determined from the curve. A uniformity series is fired with this selected weight of charge; the results must not

show a velocity variation between any two rounds of the series greater than a specified percentage, and the mean pressure obtained must fall between prescribed maximum and minimum limits.

In order for a powder to be ballistically suited to a weapon, it must give the prescribed muzzle velocity within the maximum allowable pressure limit.

Both the velocity and pressure curves must be reasonably smooth; and the pressure curve, particularly, must not show any critical point or abrupt changes.

22. Effect of Moisture and Heat.—If smokeless powder is exposed to a damp atmosphere, it will gradually absorb moisture. This tendency is very much less pronounced in FNH and NH powders. Moisture accelerates the decomposition and shortens the stability life of powder. Tests of various powders indicate clearly that the time required for definite evidence of deterioration is directly dependent upon their capacity to absorb moisture, and that the standard FNH and NH powders have greater stability and longer storage life than nitrocellulose powders.

All powder, whether in bulk or in the form of charges for a given weapon, is stored in airtight containers, as, for example, the cartridge storage cases in which the separate loading charges made up in silk cartridge bags are kept to protect them from moisture. Powder assembled in fixed ammunition would appear to be well protected from moisture by the cartridge case; but even here dampness may enter the powder through an imperfectly sealed joint between the cartridge case and the projectile. There is also the possibility of moisture entering the primer composition or the composition of a time fuze. To prevent these possibilities, each round of fixed ammunition is packed in a hermetically sealed container from which it should not be removed until shortly before use. Each round of semi-fixed ammunition is likewise packed in a hermetically sealed container.

Smokeless powder deteriorates more rapidly at high than at low temperatures. This is especially true if moisture is present. Extreme variations in storage temperature should be avoided as much as possible, as the resulting changes in dimensions of the metal containers may cause leaks and permit moisture in the air to be absorbed by the powder.

Besides accelerating the decomposition of powder, the absorption of moisture affects the ballistics. Moisture in powder decreases the rate of burning and lowers the potential as a direct function of the moisture content.

PREPARATION OF PROPELLING CHARGES

There are three forms in which ammunition is assembled for firing: fixed, semi-fixed, and separate loading.

23. Fixed Ammunition.—In fixed ammunition, the powder, cartridge case, and projectile are assembled together and loaded into the gun as a unit. The projectile is fixed rigidly to the cartridge case. The propellent charge is loaded loose in the cartridge case, and as the projectile is rigidly attached it follows that this type of ammunition does not permit the powder charge to be changed, in the field, for different range zones. Certain weapons using fixed ammunition have normal charges and reduced charges to meet different tactical requirements, but the charges are not rearranged in the field. If there is an appreciable void left in the cartridge case between the top of the propellent charge and the base of the projectile, as is the case in ammunition for the 3-in. antiaircraft gun, this void is usually filled, with cardboard spacers or distance wads, to hold the powder in a fixed position and in contact with the primer. In some fixed ammunition, a brass diaphragm was formerly soldered to the inside of the cartridge case above the powder in order to seal the round more effectively against moisture.

Except in small arms cartridges, an igniting charge of black powder is included in the primer which is inserted in the base of the cartridge case. In certain fixed rounds, an additional quantity of black powder may be used on the forward end of the charge to decrease the tendency to flash. This supplementary igniter is fastened to the inner side of the distance wad and is held securely at the forward end of the propellent charge.

24. Semi-fixed Ammunition.—Semi-fixed ammunition differs from fixed ammunition in that the propellant is divided into increments and loaded into a number of bags corresponding to the zones of fire. The increments are numbered and placed in the case in a definite order (Fig. 12). The cartridge case is not crimped or securely fastened to the projectile, and this permits removal of the projectile in the field, adjustment of the charge to the zone desired by removing one or more bags of powder, and re-assembly. The round is loaded into the gun as a unit, as in fixed ammunition.

25. Separate Loading Ammunition.—Separate loading ammunition includes all ammunition in which the propellent charge, in bags, is placed separately in the chamber of the gun after the projectile has been seated in the bore. The charge for major caliber weapons is usually divided into a sufficient number of increments to permit easy handling.

There is also another system of separate loading, prevalent abroad,

in which the propellent charge is contained in a cartridge case, the projectile being seated in the bore separately.

Charges for mobile howitzers using separate loading ammunition are assembled in a number of increments corresponding to the zones of the weapon. The charge is zoned just prior to firing by removing the sections not required for the zone. The ignition charge is contained in a pad on the end of the rear section of the charge.

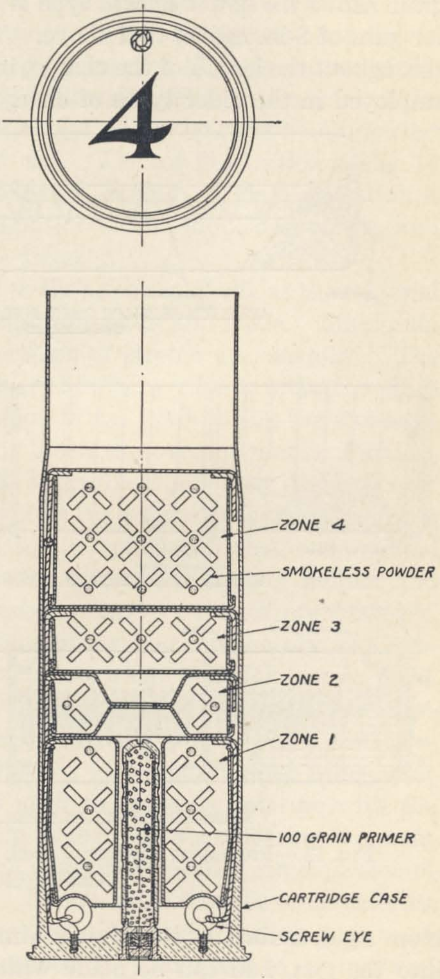

FIG. 12.—Propellent Charge for 75-mm. Pack Howitzer.

In certain weapons, such as the 240-mm. Howitzer and the 12-in. Mortars, Models 1890–1908, an aliquot part charge is used for zoning purposes. This type of charge differs from other charges which have zone increments in that the sections are of equal weight, containing the same amount of powder. It is advantageous in that the required zone charge may be obtained by removal of the proper number of increments, and additional charges may be made up from the discarded sections, which is not possible at the battery when other types with base charge and increments of varying weight are used. Aliquot part charges can be used only in those weapons where the required zoning can be obtained with increments of equal weight. This is not practicable in all weapons. The difference between the aliquot part type of charge and the multi-

section type should be noted. In the latter, the charge is also divided into a number of sections of equal weight, but only to facilitate assembly and handling.

Several types of charge are illustrated in Fig. 13. The bottom diagram shows the newer *stacked* type of charge, which has been developed for guns of 8-in. caliber and above. The grains are stacked end to end throughout the length of the charge, instead of the random arrangement employed in the older types of charges shown. The stacked charge is

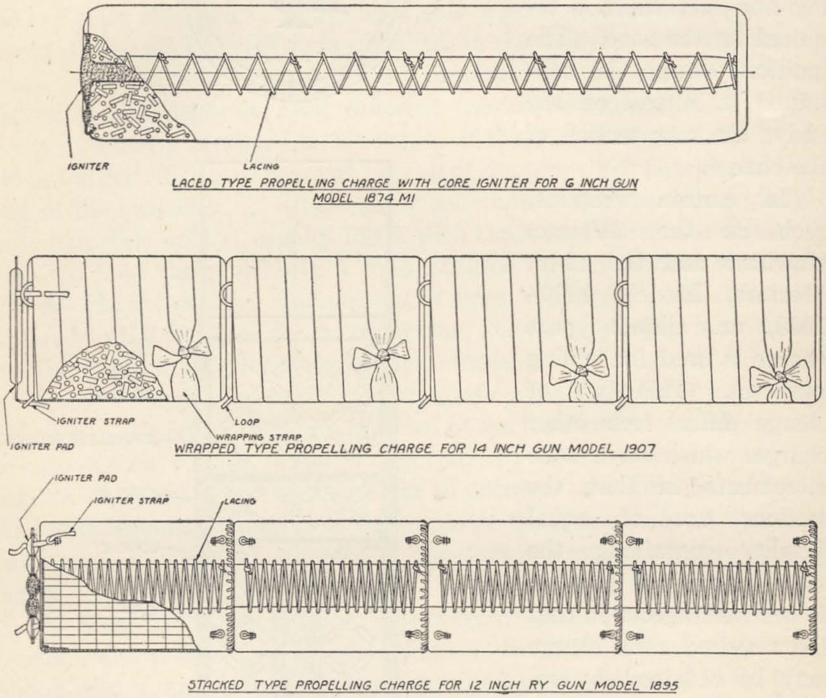

FIG. 13.—Propellent Charges, Laced, Wrapped and Stacked for Major Caliber Cannon.

more rigid, maintains its original dimensions more closely when loaded into the gun, and can be made with smaller diameter because of the reduced space required by the stacked grains. Greater uniformity of ignition from round to round is possible with this type of charge, with less variation in pressure and muzzle velocity.

26. Cartridge Bags.—Cartridge bags are made of special raw silks and are sewed with silk thread. The bags are filled by opening a seam at one end. After filling, the seam is sewed up; and the charge is laced through two pleats on the exterior or is wrapped spirally with tape to

make it firm and compact for handling (Fig. 13). The bags for major caliber guns are reinforced, to prevent bulging, by sewing a central core of cloth to the two ends on the inside of the bag. The igniting charge of black powder is contained in a pad of igniter cloth. For some cannon, the igniter element is made integral with the base section charge; for other cannon, it is assembled just prior to firing as a separate pad tied to the base section. The center core of the bag for the base charge of the 12-in. Mortar, Model 1912, is made hollow and filled with a part of the required igniting charge. The remainder of the igniting black powder is in quilted pads attached at either end. The top illustration in Fig. 13 shows a core igniter in the charge for a 6-in. gun. This distribution is considered to give more uniform ignition of the propelling charge and consequently more uniform muzzle velocity.

Several considerations have led to the selection of silk as the material from which cartridge bags and ignition pads are made. Maximum strength of cloth and minimum amount of stretch are essential. The weight and bulk of the cloth must be as low as possible in order to reduce the quantity of smoke developed upon firing. Silk, being the strongest of all combustible fibers, successfully meets these requirements. Further, animal fibers as distinguished from vegetable fibers have the property of not retaining fire or smoldering after the source of ignition has been removed. This characteristic led to the conclusion that only animal fibers could be used as substitutes for silk and the use of mohair and wool cloth was accordingly authorized. Recent experiments, however, have indicated that a special cotton cloth is also satisfactory as a substitute for silk and it is being used for cartridge bags for certain guns.

27. Flareback.—The gases resulting from burning smokeless powder are explosive, provided sufficient oxygen is added. It is thus possible, when the breech of a gun is opened immediately after firing, that enough air may enter the bore to form an explosive mixture with the gases present. Should there remain in the bore a smoldering fragment of cartridge bag, an explosion of the gases may result. An explosion of this nature is known as a flareback. Even though there be no smoldering or burning residue, the temperature of the inflammable gases may be so high that, when the breechblock is opened, they may pass to the rear and ignite on striking the air, regardless of the direction of the wind. Flames of varying length and intensity may result.

Precautions must be taken to prevent the flareback from reaching the new propelling charge, as well as to prevent serious burns to the breech detail. Certain guns are equipped with compressed-air gas ejectors which expel the gases in the bore before the breech is opened. Even when so equipped, it is essential that the bore be inspected for

burning residue in the bore or chamber before the next round is inserted. If the gun is not equipped with a gas ejector, the new propelling charge should not be brought near the breech until a wet chamber sponge has been used.

BLACK POWDER

28. Blank Ammunition for Cannon.—Blank charges for cannon are used in artillery drill and maneuvers, and for saluting. Black powder is prescribed for such charges; smokeless powder would not be satisfactory because its low rate of burning when under little confinement does not enable it to give the loud report desired with this type of ammunition.

Because of the dangers incident to the preparation of blank ammunition, and the number of accidents that have occurred both in the preparation and in subsequent firing, the practice of local loading at posts has been discontinued. The ammunition is now arsenal loaded, and issued to the service as a complete round. The black-powder charge of the specified weight is loaded into silk or muslin bags and then placed in the primed cartridge case. The round is sealed, the powder charge held in place, and the confinement necessary for a loud report obtained, by a tight-fitting chipboard cup cemented in place. When the slower burning sodium-nitrate type of commercial black powder is used, a felt wad cemented to the bottom of the cup is employed to increase the confinement.

29. Other Uses; Properties.—Black powder is a mechanical mixture usually of potassium nitrate, charcoal, and sulphur, in the approximate proportions of 74, 16, and 10. Other proportions, however, are employed for special purposes. Although classed as a low or progressive explosive, it must be regarded as dangerous and treacherous, and special precautions must be observed in its manufacture, handling, storage, and use to avoid accidents. It is quite sensitive to heat from flame, friction, or spark, and burns rapidly with evolution of extremely hot gases.

Until the latter part of the nineteenth century it was used universally as a propellant and, until the development of modern high explosives, as an explosive filler for shell, grenades, and bombs. Although superseded as a propellant by smokeless powder, and as a bursting charge except for 37-mm. L. E. Shell, it has many important military uses, such as: base charge or expelling charge in shrapnel, igniter or igniting charge for propelling charges in cannon, blank or saluting charges for cannon, time elements in powder train fuzes, smoke-puff charges, charges in practice bombs and practice grenades, and pellets for primers and fuzes.

THE PRINCIPAL MILITARY HIGH EXPLOSIVES

The principal high explosives now in use in the United States military service are:

TNT	Tetryl
Amatol	Fulminate of mercury
Ammonium picrate	Lead azide

In addition to the explosives enumerated, guncotton and nitroglycerin deserve mention.

Guncotton, a nitrocellulose of high nitration, is used in the manufacture of FNH powders. Small wisps of dry guncotton are used also as flame carriers in the central tube of shrapnel to connect the fuze with the base charge.

Nitroglycerin, when absorbed in certain solid materials, is known by the commercial name of dynamite; and is used in all kinds of blasting and demolition work. Nitroglycerin is used also in the manufacture of certain types of propellent powder known as double-base powders, and as an ingredient in certain FNH and NH compositions.

30. TNT and Amatol.—Coke, gas, ammonia, and coal tar are among the products obtained during the destructive distillation of bituminous coal. Coal tar, by further distillation and by chemical processes, can be separated into numerous compounds, most of which are combinations of carbon, hydrogen, and oxygen. These compounds removed from coal tar constitute the most important raw materials for the manufacture of dyes, medicines, and paints. Many of the coal-tar compounds are used also in the manufacture of explosives, the most important of these being:

Benzene	C_6H_6
Toluene	$C_6H_5CH_3$
Phenol	C_6H_5OH
Aniline	$C_6H_5NH_2$

Trinitrotoluene, $C_6H_2(CH_3)(NO_2)_3$, commonly designated TNT, is obtained from the substance toluene by a comparatively simple process of nitration with nitric acid. This explosive has been produced successfully in this country in large quantities.

TNT is the Army's most important high explosive. It is relatively safe in manufacture, loading, transportation, storage, and use; it is nonhygroscopic, stable, and lacks any tendency to form dangerous compounds with metals. It possesses great power and brisance. TNT is more sensitive to shock than ammonium picrate (Explosive D), and

accordingly the latter explosive is used as a shell filler for armor-piercing projectiles.

TNT, a crystalline powder of light-yellow color, resembles in appearance powdered brown sugar, although in different grades of purity its color and appearance vary. In the American service it is classified in two grades.

Grade I TNT has a minimum melting point of 80° C. It is employed alone, or mixed with ammonium nitrate to form 50–50 amatol, as a bursting charge for high explosive shell and bombs. The less pure grade II TNT, with a minimum melting point of 76° C., is used only in 80–20 amatol.

A charge of about 22 oz. of cast TNT in a 75-mm. high-explosive shell weighing 11 lb. breaks up the shell into approximately 700 fragments.

Amatol is a mixture of TNT and ammonium nitrate, NH_4NO_3. Because of the shortage of toluene during the World War and the more plentiful supply of ammonium nitrate, the mixture was developed as an emergency measure and proved to be an efficient explosive. Amatol of two kinds was used, 50–50 amatol and 80–20 amatol, the first figure representing the percentage of ammonium nitrate and the second figure the percentage of TNT.

The mixture is prepared by melting TNT and incorporating it with ammonium nitrate for a length of time sufficient to insure that each grain of ammonium nitrate is thoroughly coated with TNT. The 50–50 amatol possesses approximately the same properties and may be handled and loaded into shells in the same manner as TNT.

Amatol is used as a bursting charge for high-explosive shell and bombs.

31. Ammonium Picrate (Explosive D).—Picric acid, obtained by nitrating carbolic acid (phenol), is another name for trinitrophenol, which has the chemical formula $C_6H_2OH(NO_2)_3$. Ammonium picrate, $C_6H_2O(NH_4)\ (NO_2)_3$, or Explosive D, is formed from picric acid by mixing the acid in a hot-water solution with strong ammonia.

For many years, ammonium picrate was the secret high explosive of the United States and was known as Explosive D in order to avoid common knowledge of its chemical composition. Its particular importance as a military explosive is due entirely to its marked insensitiveness to shock and friction, which makes it especially well suited for use as a bursting charge in armor-piercing projectiles. From the standpoint of explosive strength, it is only slightly inferior to TNT.

Ammonium picrate is a powder of light-yellow color. It does not melt on heating and must be loaded in projectiles by pressing or tamping.

It has only a slight tendency to absorb moisture, but when wet it can form sensitive and dangerous picrates with copper and lead. It does not form dangerous compounds with steel, but, to avoid corrosion, the interior of the shell is covered with a suitable non-metallic paint or varnish before being filled, and a moisture-proof seal is provided at the base of the projectile.

32. Tetryl.—The high explosive, tetryl, is derived also from coal-tar products. Because its proper chemical designation is very complex [trinitrophenylmethylnitramine, $C_6H_2(NO_2)_3(NCH_3NO_2)$], this explosive is commonly known only by its designation, *tetryl.* The chemical process followed in its manufacture is complicated and results in the production of a fine, crystalline powder of yellow color, stable at all storage temperatures. Tetryl is one of the most powerful of all military high explosives. Its strength and brisance would seem to adapt it for use as a bursting charge, but its sensitiveness is such that if used as a shell filler it might not withstand the shock of discharge of the gun and a premature explosion would result. However, when highly compressed, and securely confined in a container to prevent movement or *set-back* action, a relatively small quantity may be used safely as a *booster charge.* As a booster it is readily exploded by the detonator of the fuze, and the violence of its explosion insures a high order of detonation of the bursting charge.

Tetryl is the standard booster explosive. During the World War it was employed to a considerable extent in combination with TNT; but these boosters were unsatisfactory, and tetryl alone is now used.

33. Mercury Fulminate.—Fulminate of mercury is the most sensitive explosive used in our service; it has been the detonating agent commonly employed in the explosive train to initiate the detonation of other high explosives. It detonates completely when brought to its ignition temperature by flame or other means, and also is readily detonated by friction or shock. Its characteristic properties make it suitable for use as an ingredient in friction and percussion priming compositions, and in detonators.

The raw materials required for manufacture are metallic mercury, nitric acid, and ethyl alcohol. The manufacturing process is quite simple, although also quite hazardous; it is generally prepared in relatively small lots. The product is a heavy, crystalline solid, nearly white in color. It is essential that it have a very high degree of purity.

Because of its extreme sensitiveness to shock or friction, mercury fulminate is never stored or transported in the dry state, except when loaded into detonators, fuzes, and primers. It is always stored and shipped thoroughly saturated with water. The presence of even small amounts

of moisture greatly reduces its sensitiveness and efficiency. Although generally stable for long periods, it deteriorates fairly rapidly when exposed to elevated temperatures, and it has a tendency to react with brass or copper, forming copper salts which are more sensitive than the fulminate itself.

34. Lead Azide.—Lead azide [$Pb(N_3)_2$] is a fine, cream-colored compound which is gradually coming into use as a standard detonator explosive, replacing mercury fulminate for certain uses. It is less sensitive to shock than the fulminate, flashes at a much higher temperature, is more stable, and can be stored for indefinite periods even at elevated temperatures without deterioration. Its sensitiveness and efficiency are not so much affected by absorption of small amounts of moisture, and it has less tendency than the fulminate to react with metals. It reacts with copper so readily, however, that it is usually loaded into aluminum detonator capsules.

Lead azide is much more readily detonated by flame than by shock or friction. When used in the explosive train to initiate the detonation of the booster, it is brought to the ignition temperature by flame from some other element. For example, when used in a detonator which is to be exploded by the action of a firing pin, it must have a covering or priming charge of some other suitable sensitive explosive.

Lead azide may be stored under water or alcohol. Like mercury fulminate, it should not be stored with any other explosives which might be exploded by its detonation.

35. Other Explosives.—Nitrostarch explosives were developed during the World War as a substitute for TNT, because of a deficient toluene supply. Investigation showed the nitrostarch explosives to be entirely suitable for trench warfare purposes, and to have certain advantages over TNT on account of low cost, insensitiveness to friction and impact, and ample supply of raw material.

Starch is manufactured by grinding roots, plants, or seeds, and eliminating the cell tissue. The material remaining is starch, and is pressed into the required form and dried. Its chemical formula is similar to cellulose, but the arrangement of atoms in the molecules is different.

When nitrated, starch becomes a high explosive; but as used in the military service during the World War, nitrostarch explosives consisted of only 40 per cent pure nitrostarch mixed with ammonium nitrate and other substances. The nitrostarch explosive was used as the bursting charge for hand grenades, rifle grenades, and trench-mortar shells.

Because of the rigorous conditions of protracted storage to which nitrostarch explosives were subjected, the charges have become deficient

in stability so that this explosive has been entirely withdrawn from service. It may be again used, however, in case of future need.

Picric acid [trinitrophenol, $C_6H_2OH(NO_2)_3$] has been used extensively as a military explosive by foreign nations. Because of the availability of raw materials, the use of picric acid explosives by the United States might become necessary in case of war, in the event of shortage of materials for standard explosives.

Tridite, a mixture of trinitrophenol and dinitrophenol, might be used as an emergency explosive. The trinitrophenol is obtained by the nitration of phenol, produced either as a coal-tar product or synthesized from benzene, and is readily available. The dinitrophenol also is made from benzene but by a different process of manufacture. The explosive properties of Tridite are almost identical with those of TNT. The mixture can be cast, and the charge is free from exudation. The precautions to be taken in the use of Explosive D apply equally to Tridite.

36. Storage of Explosives.—Detailed regulations covering the storage of ammunition and explosives at military establishments are published by the War Department. To reduce storage hazards, only certain specified types may be stored together in the same magazine, and the total amount of explosives permitted in a single magazine is usually prescribed. Depending upon the nature of the magazine, and the type and amount of explosives stored therein, a table of minimum distances is prescribed, setting forth the minimum intervals between magazines, and distances from magazines to inhabited buildings, public highways, and public railways.

Explosives and ammunition should not be stored in buildings used for other purposes. Standard magazines constructed in accordance with War Department specifications should be used when practicable. Magazines and surrounding area should be kept scrupulously clean, all practicable precautions should be taken against fire, and a climb-proof fence should surround the area. All persons working within or around magazines, or engaged in handling explosives, should be familiar with the instructions governing storage and handling, and their activities should be carefully supervised. Loading, repacking, maintenance, and salvage operations must be conducted in accordance with recognized safety standards, and should be performed as far from the magazine as may be necessary.

NITROGEN FOR EXPLOSIVES

37. General.—Practically all military explosives are formed by treating with nitric acid a wide variety of organic and inorganic substances, such as toluene, glycerin, phenol, mercury, cellulose, starch, and many others.

From a broad national-defense viewpoint, an adequate supply of nitrogen in usable form is essential not only for the manufacture of military explosives, and those commercial explosives required in the construction and mining industries and for other purposes, but also for use in other important industries. In the form of nitric acid, vast quantities are required by the dye industry and in the manufacture of plastic materials, such as celluloid and pyroxylin, and of other commercial products. In the form of fertilizer, nitrogen is essential to agriculture. Nitrogen is used in many forms by many industries.

38. Sources of Nitrogen.—Nitrogen occurs chiefly in the form of the free element, which constitutes about 80 per cent of the earth's atmosphere. Because of the general instability of many of its compounds and the readiness with which they are decomposed, the amounts of nitrogen in the earth's crust are relatively very small. Animal and plant tissues constitute another source of supply.

Organic Nitrogen.—Sources for the supply of organic nitrogen include manure, miscellaneous farm refuse, and such plant and animal tissues and refuse as fish scrap, bone meal, cottonseed meal, tankage from slaughter houses, and other organic by-products of industry. Organic nitrogen supplies only a part of the fertilizer required by agriculture. Other nitrogenous fertilizers and industrial nitrogen are supplied by other methods and from other sources.

Inorganic Nitrogen.—The three sources of inorganic nitrogen are (1) natural nitrate beds found in certain countries, (2) by-product coke ovens, and (3) nitrogen fixation plants.

For many centuries, the nitrate beds of India supplied the potassium nitrate used in the manufacture of black powder and for other industrial purposes. From 1830 to 1919, Chile saltpetre or sodium nitrate, found in large deposits in Chile and Peru, was the chief source of industrial and fertilizer nitrogen. During the World War the United States was almost entirely dependent upon this source for the nitrates required in the production of explosives and for other essential industrial uses. Since that time, competition from the synthetic nitrogen industry has caused a decline in the production of Chilean nitrates, and only a small part of the world's requirements come from that source.

Coke is formed by the destructive distillation of coal, which contains from 1 to 2 per cent of nitrogen. Formerly, the coke required by the steel industry was produced in the old "beehive" type of oven, which permitted all the products of distillation, including nitrogen in the form of ammonia, to pass off into the air as waste. The modern "by-product" type of oven permits recovery of the ammonia and many other valuable by-products. In the United States, transition from the old to the new

type of oven was accelerated greatly by the World War, and today this industry has an annual capacity of approximately 200,000 tons of nitrogen.

The third and most important source of supply is the nitrogen fixation plant, in which nitrogen of the air is fixed into usable nitrogenous compounds by chemical and electrochemical processes. The factors responsible for the intensified search for practicable methods of fixing atmospheric nitrogen, and for the rapid development of the industry, include the following: (1) increased requirements of the world for nitrogen for agriculture, for rapidly growing chemical industries, and for the production of military and commercial explosives; (2) the undesirability, from both military and economic standpoints, of depending upon imports from Chile to meet vital needs. The growth of the industry has been so rapid that the world's synthetic nitrogen capacity is ample to meet all normal and peace time needs. The two processes of industrial importance are the *Cyanamide* process and the *Haber* process or one of its modifications.

39. Cyanamide Process.—In this process, gaseous nitrogen obtained by the distillation of liquid air is passed through powdered calcium carbide at a high temperature, producing calcium cyanamide ($CaCN_2$). One disadvantage is that to produce calcium carbide from coke and lime requires high temperatures reached only by electric furnaces, and this limits production of cyanamide to those countries where abundant and cheap hydroelectric power is available.

Cyanamide contains about 35 per cent nitrogen, and is an excellent fertilizer used abroad extensively. Also, ammonia can be produced by the simple action of steam on powdered cyanamide. From ammonia there can be produced nitric acid to meet military and industrial needs, ammonium nitrate to be used with TNT in producing amatol, and various ammonium salts for fertilizer.

Nitrate Plant No. 2, at Muscle Shoals on the Tennessee River, was built by the United States during the World War to produce nitrogen by the cyanamide process. Since it was intended primarily as a source of supply for ammonium nitrate required for explosives, it contained an ammonia oxidation section. The plant has not been operated since the war, and there is no calcium cyanamide manufactured in the United States at the present time.

40. Haber Process.—The Haber process and its later modifications produce synthetic ammonia by the combination of pure gaseous nitrogen and hydrogen, effected under high pressure and high temperature in the presence of a suitable catalyst. All other processes employed for the synthesis of ammonia are mere modifications of the Haber, differing primarily in the temperatures, pressures, and catalysts used.

The first step in the process is to obtain the necessary pure elementary gases. The nitrogen is generally produced by the distillation of liquid air, but also may be obtained by passing air through red-hot coke, producing a mixture of nitrogen and carbon dioxide, from which the carbon dioxide can be removed readily by bubbling through water. Several methods are used to produce hydrogen. The most widely used method involves the passing of steam through red-hot coke, forming a mixture of hydrogen, carbon monoxide, and other gases. The mixture is again mixed with steam and passed over a catalyst, when carbon dioxide and more hydrogen are produced. The CO_2 and other undesirable gases are then removed by bubbling through water. Hydrogen can also be obtained from the gas from by-product coke ovens, a gas which contains about 50 per cent hydrogen. The remainder of the gas is made up largely of gaseous hydrocarbons which can be liquefied under high pressure and low temperature. The third source of supply is electrolytic hydrogen produced by the decomposition of water by electricity. This is used only where electric power is very cheap.

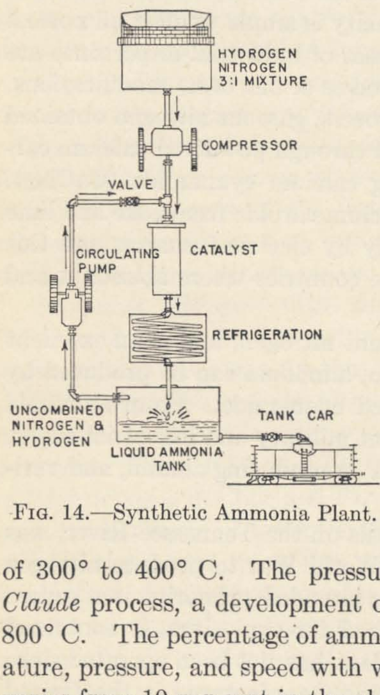

FIG. 14.—Synthetic Ammonia Plant.

Figure 14 shows schematically the essential features of a synthetic ammonia plant. The proper mixture of gaseous hydrogen and nitrogen is compressed at pressures from 100 to 400 atmospheres and passed through the catalyst chamber, which is initially heated to a temperature of 300° to 400° C. The pressures and temperatures employed in the *Claude* process, a development of the Haber, are 900 atmospheres and 800° C. The percentage of ammonia conversion depends on the temperature, pressure, and speed with which the gases are passed through, and varies from 10 per cent in the older processes to 40 per cent in the most modern. The ammonia is liquefied by refrigeration and the uncombined gases are then sent back again over the catalyst by means of a circulating pump.

Nitrate Plant No. 1, using the Haber process, was built by the United States during the World War at Sheffield, Ala. It contained an ammonia oxidation section for the manufacture of nitric acid. The plant has not been operated since the war and, like the Muscle Shoals plant, is more or

less obsolete. However, there has been a very great commercial development of nitrogen fixation in this country since the World War. The resulting synthetic ammonia capacity, together with the by-product ammonia capacity, is in excess of normal peace time needs. By reasonable expansion of the fixed nitrogen industry, it is anticipated that the war needs of the country could be met, and that modernization and operation of the government plants would not be necessary. The ammonia oxidation sections of the plants, however, constitute a real military asset, and they could be placed in operation quickly for the production of nitric acid and ammonium nitrate from ammonia procured from other sources.

41. Production of Nitric Acid.—Formerly, all nitric acid was produced by the action of sulphuric acid on Chilean nitrate,

$$H_2SO_4 + 2NaNO_3 = 2HNO_3 + Na_2SO_4$$

A large part of the nitric-acid supply is still produced by this method, using domestic synthetic sodium nitrate. However the ammonia oxidizing process, such as used in the government plants mentioned, is gradually replacing the other process.

To produce nitric acid from ammonia, air containing 10 per cent of ammonia is passed into a converter, the essential part of which is a cylinder of platinum gauze through which the mixture must pass. When the ammonia comes into contact with the cylinder a very rapid reaction takes place, with liberation of considerable heat,

$$4NH_3 + 5O_2 = 4NO + 6H_2O$$

A second reaction takes place beyond the gauze, the nitric oxide slowly uniting with additional oxygen,

$$4NO + 2O_2 = 4NO_2$$

The nitrogen dioxide is then passed into absorption towers filled with material such as quartz or pieces of earthenware over which water trickles. Dilute nitric acid is thus formed. By mixing it with sulphuric acid and then distilling, pure concentrated nitric acid may be obtained. By treating it with ammonia or soda ash, ammonium nitrate or sodium nitrate may be produced for use in explosives.

CHAPTER II

THE THEORY OF EXPLOSIVES

42. Research and Development.—The development of new and improved types of ammunition and ammunition components requires a continuous program of research and investigative effort concerned with new explosives and explosive train combinations. This involves a comparison of new or proposed types and combinations with those which are standard or accepted and necessitates a determination of relative characteristics and qualities as between the new and the old. In the last analysis, adoption of a particular explosive for a given use will be based upon proving-ground and service tests. Preceding these, however, preliminary determination of the characteristics of an explosive may be investigated by theoretical calculations and comparative qualities established by laboratory and other experimental tests.

Thermochemistry is concerned with the heat effects and internal energy changes accompanying chemical reaction. In military explosives, the explosion consists of a series of reactions, highly exothermic in their summation, involving decomposition of the ingredients and recombination to form the products of explosion. Explosive reactions are determined either from known chemical laws or by analysis of the products. These products of explosion are those remaining in a closed calorimetric bomb after cooling to atmospheric temperature and after considerable reduction of pressure. The actual composition of the gases at maximum temperature and pressure is unknown; it is only the final mixture, resulting on recombination after decomposition and dissociation, which may be analyzed. Knowing the chemical reaction, and with other data obtained theoretically or experimentally, theoretical deductions can be made concerning the characteristics of the explosive. Although not conclusive, such calculations provide data on which to base investigations and may obviate the necessity of exhaustive experimental tests.

The characteristics of an explosive which are of basic importance are as follows:

a. Heat of explosion.

b. Volume of products of explosion.

c. Rapidity of reaction.
d. Maximum temperature of reaction.
e. Maximum pressure developed in a closed chamber.

The quantity of heat given off by the explosive in a closed chamber and the volume of gases produced may be measured experimentally by use of the bomb calorimeter. Also, knowing the chemical reaction and the heats of formation of the explosive itself and of the products of explosion, the volume of the gases and the quantity of heat liberated at constant pressure may be calculated. Thus, the potential of the explosive or its capacity for doing work may be determined practically by experiment and theoretically by calculation.

The rapidity of reaction of an explosive may be determined directly, by experiment, in high explosives. This is termed the rate of detonation of the explosive, and is a measure of its brisance. The rate of combustion of propellants varies with the specific rate of burning and the pressure, and may be computed by empirical formulas based upon experimentally-determined values of the influencing factors. The specific rate of burning is the depth or thickness of the layer burned, measured normal to the burning surface, in unit time under specified conditions. Pressures may be measured directly or computed theoretically. The rate of burning of a propelling charge profoundly influences the ballistic effects produced in a weapon.

No method has been developed for direct determination of the temperature of explosion. Its value is calculated theoretically from specific heat, heat of explosion, and other available analytical data.

The pressure developed by an explosion in a closed chamber may be measured directly by a suitable gage or calculated by use of the gas laws and known data.

It is to be noted that certain thermochemical characteristics of propellants, which affect ballistic performance, cannot be measured practically under gun-firing conditions and, because of the physical and thermochemical variables involved, these must vary from those characteristics determined theoretically or by calorimetric measurements in the laboratory. The data obtained from the latter are of greater value in the development of new compositions and the comparison of compositions than in designing a powder to fit a gun. Eventually, however, the accumulation and correlation of data may permit the establishment of direct and precise relationships between determinable thermochemical characteristics and actual ballistic characteristics.

43. Physical Testing.—Laboratory methods are employed to determine other qualities and characteristics of explosives and to permit

comparison of explosives proposed for a particular use with other explosives whose characteristics are known. Such preliminary comparison tests include the following:

High explosives:

Sensitivity to ignition or explosion by heat.
Sensitivity to detonation by impact.
Sensitivity to detonation by initial detonating agents.
Brisance, or relative shattering capacity.
Initiating value, or ability to detonate other explosives.

Primer compositions:

Sensitivity to impact.
Impulse value, or shock effect produced.
Gas volume produced.
Relative ability to ignite black powder.
Effect on form, volume, and duration of black powder flame.

Laboratory tests are normally followed by tests on a larger scale to confirm previous results and to determine other qualities. They may include:

Explosive train tests, to determine the functioning and effectiveness of each element in the explosive train.

Set-back tests, to insure safety and certainty of action of all components after undergoing setback in the gun or set forward on impact.

Fragmentation test, to determine the effectiveness with which a high explosive filler will fragment standard shell.

Trauzl lead block test, to establish the comparative disruptive effect of an explosive.

Ballistic mortar test, to establish relative explosive strength.

Many other factors which enter into the question of the suitability of an explosive for military use, as, for example, stability or resistance to gradual decomposition by heat, must be considered prior to its adoption. The determination of the relative merits of two competing explosives requires consideration of all factors, test results, and available pertinent data.

THEORETICAL DETERMINATIONS

44. Definitions; Terms.—An explanation of the less familiar terms used in the discussion of this subject follows.

A *gram molecule* of a compound is a definite weight of that compound; it is the gram-molecular weight, or the weight in grams numerically

equal to its molecular weight. Thus, the molecular weight of mercury fulminate, $Hg(CNO)_2$, is 284.6, and one gram molecule of this explosive is 284.6 grams. The term will be applied also to a mixture, indicating a weight in grams equal to the sum of the molecular weights of as many molecules of each ingredient as appear in the formula of the mixture. Thus, a gram molecule of black powder, $10KNO_3 + 3S + 8C$, is $(10 \times 101.1 + 3 \times 32 + 8 \times 12)$ grams, or 1203 grams. Similarly, a gram molecule of a mixture of TNT and ammonium nitrate represented by the formula $C_6H_2(NO_2)_3CH_3 + 3NH_4NO_3$ is $(227.1 + 3 \times 80)$ grams, or 467.1 grams.

A *small calorie* is the quantity of heat required to raise the temperature of one gram of water (one cubic centimeter) from 14.5° C. to 15.5° C. A *large calorie* is 1000 small calories.

The mechanical equivalent of a large calorie, that is, the corresponding amount of work, is approximately 4270 kilogram decimeters.

The metric system of weights and measures was used in the original investigation of the theory of explosives, and all tabulations of values of factors and constants are given in metric units. The determination of our problem is accordingly simplified by using metric units for our calculations and then, if desirable, by transforming the results into English units.

When a chemical compound is formed, the reaction either absorbs or gives off heat. The quantity of heat absorbed or given off during transformation is called the *heat of formation.* The heats of formation for solids and gases found in explosive reactions have been determined for an initial temperature of 15° C. and atmospheric pressure, and are tabulated in units of large calories per gram molecule. They are listed in a table of the Appendix. Where a negative value is given, it indicates that heat is absorbed during the formation of the compound from its elements.

The *principle of the initial and final state* may be expressed as follows: The quantity of heat liberated or absorbed in any chemical modification of a system depends solely upon the initial and final states of the system, provided the transformation takes place at constant volume or at constant pressure. It is completely independent of the intermediate transformations and of the time required for the reactions. From this it follows that the heat liberated in any transformation accomplished through successive reactions is the algebraic sum of the heats liberated or absorbed in the different reactions. We may therefore consider the formation of an explosive as an intermediate reaction in the formation of the products of explosion from simple elements. If, after the explosion of a substance, we subtract (algebraically), from the total heat

liberated when the products of explosion are formed from their elements, the heat liberated or absorbed on the original formation of the explosive from its elements, the difference will be the heat liberated in the reaction of the explosion. The effect of this principle will be first observed in the calculation of the quantity of heat liberated at constant pressure.

The *specific heat* of a substance is the amount of heat required to raise the temperature of a unit weight of the substance one degree, under defined conditions of temperature, pressure, and volume.

The specific heat of solids may be assumed to be constant, provided we do not approach too near their melting points or their dissociation temperatures. A similar assumption may be made as to the specific heats of liquids, except in ranges close to their freezing, boiling, or dissociation temperatures. The specific heats of gases vary with the temperature, and the specific heat of any gas at constant pressure, c_p, is always greater than that at constant volume, c_v, since in the former case the work of expansion is involved.

The *molecular specific heat* of a gas is the quantity of heat necessary to raise the temperature of a gram molecule of the gas 1° C. It also varies with the temperature, and is greater at constant pressure than at constant volume.

The *specific volume* of a gas is the volume of a unit weight of a gas at 0° C. temperature and normal atmospheric pressure.

The *molecular volume* is the volume of a gram molecule of the gas under the same conditions of temperature and pressure.

The *co-volume* of a gas is defined as the smallest volume to which a unit weight of the gas can be compressed. For the gaseous products of explosion, the co-volume may be assumed to be 1/1000 of the specific volume.

The *specific gravity* of an explosive is the ratio of its weight to the weight of an equal volume of water at standard temperature. The *density* of an explosive is its mass per unit volume. If the gram is used as the unit of mass and the cubic centimeter as the unit of volume, the numerical expressions for density and specific gravity referred to water at 4° C. are the same.

The *density of loading*, used in calculating pressure in a closed chamber, is the ratio between the weight of the explosive and the weight of the volume of water which would fill the total chamber in which the charge is loaded.

The *potential* of an explosive is the total work that can be performed by the gas resulting from its explosion, when expanded adiabatically from its original volume until its pressure is reduced to atmospheric pressure and its temperature to 15° C. The potential is therefore the

total quantity of heat given off at constant volume when expressed in equivalent work units.

An explosion may occur under two general conditions: the first, *unconfined*, as in the open air where the *pressure* (*atmospheric*) is constant; the second, *confined*, as in a closed chamber where the *volume* is constant. The same amount of heat is liberated in each case, but in the unconfined explosion a certain amount is used up in pushing back the surrounding air, and therefore is lost as heat. In a confined explosion, however, such as occurs in the powder chamber of a firearm, practically all the heat of explosion is conserved as useful energy. If we calculate the quantity of heat liberated at constant volume from a weight of explosive under adiabatic conditions and convert that heat into equivalent work units, we shall have found the potential, or capacity for work, of that weight of the explosive.

Let Q_{mp} represent the total quantity of heat given off by a gram molecule of explosive at 15° C. and constant pressure (atmospheric),

Q_{mv} represent the total heat given off by a gram molecule of explosive at 15° C. and constant volume,

W represent work of pushing back the surrounding air in unconfined explosion,

E represent the mechanical equivalent of heat (assumed to be 4270 kilogram decimeters per large calorie).

Then,

$$Q_{mv} = Q_{mp} + W/E \tag{1}$$

from which the potential, EQ_{mv}, of a gram molecule of an explosive may be obtained. From this the potential of any weight of the explosive may be determined.

45. Quantity of Heat Liberated at Constant Pressure (Q_{mp}).—The quantity of heat liberated at constant pressure is determined directly from the chemical formula of the substance and the chemical formulas of the products of explosion, together with the tabulated heats of formation. The problem is simply to add together the heats of formation of the products of explosion and to subtract from this total the heat of formation of the explosive itself.

The chemical reaction representing the explosion of nitroglycerin, with the total molecular weights and heats of formation of the explosive and of the products of explosion indicated, is

Molecular weights	454.2	264	90.1	84.1	16
	$2C_3H_5(NO_3)_3$	$= 6CO_2$	$+ 5H_2O$	$+ 3N_2$	$+ \frac{1}{2}O_2$
Heats of formation	170.6	566.3	289		

This reaction can be expressed by saying that 2 gram molecules (or 454.2 grams) of nitroglycerin produce upon explosion 6 gram molecules (or 264 grams) of CO_2; 5 gram molecules (or 90.1 grams) of H_2O (gaseous); 3 gram molecules (or 84.1 grams) of N_2; and $\frac{1}{2}$ gram molecule (or 16 grams) of O_2. The heats of formation in large calories per gram molecule are: nitroglycerin, 85.3; CO_2, 94.39; water (gaseous), 57.81. The nitrogen and oxygen have not combined in the reaction and therefore do not give off heat. Therefore, we have

$$2Q_{mp} = (6 \times 94.39) + (5 \times 57.81) - (2 \times 85.3) = 684.8 \text{ large calories}$$

which is the number of large calories given off on the explosion of 2 gram molecules (or 454.2 grams) of nitroglycerin. Therefore, for 1 gram molecule (or 227.1 grams),

$$Q_{mp} = 342.4 \text{ large calories}$$

The quantity of heat just calculated is under the conditions for which the heats of formation were originally determined, the assumption being made that the products of combustion have been reduced to atmospheric pressure and to a temperature of 15° C.

It will be noted that the heat of formation of water has been taken as that for water gaseous. At 15° C. and atmospheric pressure water is liquid, but at the moment of maximum pressure and temperature during explosion, and at all working temperatures at which we are interested practically in investigating the products of explosion, water is gaseous. Accordingly, in calculating the heat liberated under conditions of explosion, water is considered to exist as a gas.

For any other weight of explosive, such as a kilogram, the procedure is as follows:

Let Q_{kp} represent the total quantity of heat given off by a kilogram of explosive at 15° C. and constant pressure (atmospheric).

Then,

$$Q_{kp} = 342.4(1000/227.1) = 1507.7 \text{ large calories}$$

46. Volume of Gas.—The law of Avogadro, determined experimentally, states that equal volumes of all gases contain the same number of molecules, under the same conditions of temperature and pressure.

From this law it follows that the molecular volume of one gas is exactly equal to the molecular volume of any other gas.

The *molecular volume* of all gases at 0° C. and under normal atmospheric pressure was found to be very nearly 22.4 (actually 22.412) liters or cubic decimeters.

Thus, considering again the nitroglycerin reaction,

$$2C_3H_5(NO_3)_3 = 6CO_2 + 5H_2O + 3N_2 + \tfrac{1}{2}O_2$$

we see that two gram molecules of nitroglycerin on explosion produce in the gaseous state: 6 gram molecules of CO_2; 5 gram molecules of H_2O; 3 gram molecules of N_2; and $\frac{1}{2}$ gram molecule of O_2. Since a molecular volume is the volume of one gram molecule of gas, two gram molecules of the explosive substance, nitroglycerin, produce $6 + 5 + 3 + \frac{1}{2} = 14\frac{1}{2}$ molecular volumes of gas; and these molecular volumes at 0° C. and atmospheric pressure form an actual volume of $14\frac{1}{2} \times 22.4 = 324.8$ liters or cubic decimeters of gas.

If n_m is the number of molecular volumes of gas resulting from the explosion of one gram molecule of explosive,

n_k is the number of molecular volumes resulting from one kilogram of explosive,

V_m is the volume of gas in liters resulting from one gram molecule of the explosive at any stated temperature,

V_k is the volume of gas in liters resulting from one kilogram at any stated temperature.

then,

$n_m \times 22.4 = V_m$, for 0° C. and normal atmospheric pressure

and

$n_m = 14\frac{1}{2}/2 = 7\frac{1}{4}$ molecular volumes.

$V_{m0} = 7\frac{1}{4} \times 22.4 = 162.4$ liters, since one molecular volume of any gas at 0° C. and atmospheric pressure always equals 22.4 liters

$n_k = 7\frac{1}{4} \times 1000/227.1 = 31.92$ molecular volumes

$V_{k0} = 162.4 \times 1000/227.1 = 715.1$ liters

The above value of V_m or $22.4 \times n_m$, is the volume of gaseous products from one gram molecule of the explosive at atmospheric pressure and 0° C. To determine the value of V_m at 15° C., which is the temperature for which the heats of formation were calculated and tabulated, we must make use of the law of Gay-Lussac for perfect gases. This law states that at a constant pressure a perfect gas expands 1/273 of its volume at 0° C. for each degree of rise in temperature.

Therefore, at 15° C., the volume of gas from one gram molecule of any explosive becomes,

$$V_{m15} = 22.4(1 + \tfrac{15}{273}) \times n_m = 23.63 \times n_m \qquad (2)$$

47. External Work Performed in Expansion.—Immediately upon explosion in the open air, the volume of an explosive substance is greatly increased. If we find the quantity of heat consumed in the work of pushing back the surrounding air, and add this amount to Q_{mp}, we shall have found Q_{mv}. The external work performed in the expansion of the gas may be determined as follows:

Let p represent the pressure per unit of area and V the volume of any given weight of the gas at any pressure, p, and any temperature,

s represent the surface of the envelope enclosing the gas, and u the travel of the surface, s, as the gas expands.

The work of expansion evidently is given by

$$W = \int psdu = \int pdV \tag{3}$$

In this case p is the constant normal atmospheric pressure of 103.33 kilograms per square decimeter, and for the work performed in expansion we have

$$W = \int_{V_1}^{V_2} pdV = p\int_{V_1}^{V_2} dV = p(V_2 - V_1) \tag{4}$$

in which V_1 represents the volume of the solid explosive and, V_2 the volume of the gaseous products. Here V_1 is negligible compared with V_2 and may be disregarded, therefore

$$W = pV_2 \tag{5}$$

From Eqs. (2) and (5), we have,

$$W = pV_m = 103.33 \times 23.63 \times n_m = 2441.69n_m \text{ kilogram decimeters} \tag{6}$$

for the work of expansion of one gram molecule at atmospheric pressure and 15° C.

48. Quantity of Heat Liberated at Constant Volume (Q_{mv}).—The equivalent quantity of heat consumed in expansion at 15° C. and under constant atmospheric pressure, but available in confined explosion, is then

$$W/E = 2441.69n_m/4270 = 0.572n_m \text{ large calories} \tag{7}$$

Substituting this value in Eq. (1), we have

$$Q_{mv} = Q_{mp} + 0.572n_m \tag{8}$$

For the nitroglycerin reaction,

$$Q_{mv} = 342.4 + (0.572 \times 7\tfrac{1}{4}) = 346.5 \text{ large calories}$$

and

$$Q_{kv} = 346.5 \times 1000/227.1 = 1525.8 \text{ large calories}$$

49. Potential.—We have now shown how we may determine, theoretically, the quantity of heat given off at constant volume on the explosion of any substance whose chemical reaction is known. All these calculations are made on a basis of cooling the products of explosion to 15° C. Practically, the determination is accomplished by the use of the familiar bomb calorimeter immersed in a known quantity of water at a known temperature.

Having determined Q_{mv}, the potential of any weight of the explosive can now be found. For one gram molecule of nitroglycerin,

$$Q_{mv} \times E = 346.5 \times 4270 = 1{,}479{,}555 \text{ kilogram decimeters}$$

Similarly, the potential of one kilogram is

$$346.5 \times 4270 \times 1000/227.1 = 6{,}514{,}993 \text{ kilogram decimeters}$$

TEMPERATURE OF EXPLOSION IN CLOSED CHAMBER

50. Temperature of Explosion.—In the investigation of an explosive, it is of importance to know to what temperature the products of explosion will be raised. These products are essentially a mixture of gases, each of which has a definite specific heat which has been determined experimentally. If the specific heat of the products were constant, the quantity of heat liberated at constant volume by the explosion of a gram molecule of the explosive would be equal to the molecular specific heat multiplied by the rise in temperature. However, the specific heat is not constant, but increases with the temperature. It was assumed by the investigators, Mallard and Le Chatelier, that the specific heat of any gas varies in the manner represented by the equation

$$C_{mv} = a + bt \tag{9}$$

in which t = the rise in temperature above 0° C.

C_{mv} = mean molecular specific heat at constant volume between 0° and t° C.

a = molecular specific heat at 0° C.

b = increment of the mean molecular specific heat for each degree of rise in temperature.

It then was necessary to determine experimental values of a and b that would fulfill the assumed equation. After laborious investigation,

the following values, in *small calories* per gram molecule, were determined:

H_2	$a = 4.87$	$b = 0.00082$
O_2	$a = 4.98$	$b = 0.00086$
N_2	$a = 4.86$	$b = 0.00086$
H_2O	$a = 6.58$	$b = 0.0029$
CO	$a = 4.84$	$b = 0.00086$
CO_2	$a = 6.24$	$b = 0.0030$
NO	$a = 4.99$	$b = 0.00086$
NH_3	$a = 6.73$	$b = 0.0060$
CH_4	$a = 7.23$	$b = 0.013$

The values of Q_{mv} are based on experimental results in which the gases were cooled to 15° C., whereas the foregoing values of a and b have been determined at 0° C. Also, Q_{mv} has been determined in large calories, and its value must be multiplied by 1000 to get it in the same units as a and b, that is, in small calories. Therefore, the total heat given off by a gram molecule of explosive at constant volume and at 0° C. is $1000Q_{mv}$ plus the amount of heat which would have been obtained if the gases had been cooled to 0° C. This latter amount is $(a + 15b)15$ and the total heat becomes

$$1000Q_{mv} + 15(a + 15b)$$

The total heat which would have been obtained if the gases had been cooled from $t°$ to 0° is also the product of the temperature by the mean molecular specific heat from 0° to $t°$, or

$$(a + bt)t$$

Therefore,

$$(a + bt)t = 1000Q_{mv} + 15(a + 15b) \tag{10}$$

Solving for t, we obtain

$$t = \frac{-a + \sqrt{4000bQ_{mv} + (a + 30b)^2}}{2b} \tag{11}$$

The temperature of explosion of nitroglycerin is determined as follows:

$$2C_3H_5(NO_3)_3 = 6CO_2 + 5H_2O + 3N_2 + \tfrac{1}{2}O_2$$

$$2a = (6 \times 6.24) + (5 \times 6.58) + (3 \times 4.86) + (0.5 \times 4.98) = 87.41$$

$$a = 43.705$$

$$2b = (0.003 \times 6) + (0.0029 \times 5) + (0.00086 \times 3.5) = 0.03551$$

$$b = 0.01775$$

$$t = \frac{-43.705 + \sqrt{4000 \times 0.01775 \times 346.5 + (43.705 + 30 \times 0.01775)^2}}{2 \times 0.01775}$$

$$t = 3360° \text{ C}$$

$$T = 3360° + 273° = 3633° \text{ absolute}$$

51. Temperature When Solid Products Are Formed.—In those explosives which are not entirely converted to gas, the heat absorbed by the solid products must be considered in determining the temperature of explosion. Equation (11) was derived on the basis of all the products of explosion being gaseous. Assume that in addition to the gases there are x gram molecules of a solid product having a molecular specific heat of h. In Eq. (9) C_{mv} will represent the mean molecular specific heat of all the products, and the value of a for the mixture of gases must be increased by the quantity xh. The value of b is not affected if it be assumed that the specific heat of a solid does not vary with the temperature. Accordingly, Eq. (11) may be used to determine the temperature of explosion when solid products are formed, it being necessary only to use a value of a for all the products.

Example.—The explosion of ammonium picrate is represented by the following reaction:

$$2C_6H_2(NO_2)_3ONH_4 = 3CO_2 + 8CO + 6H_2 + 4N_2 + C$$

Considering carbon as a solid product, with a specific heat of 1.98 per gram molecule, then

$$2Q_{mp} = (3 \times 94.39) + (8 \times 26.43) - (2 \times 78) = 338.61 \text{ large calories}$$

$$Q_{mp} = 169.3 \text{ large calories}$$

$$Q_{mv} = 169.3 + (0.5724 \times 21/2) = 175.3 \text{ large calories}$$

$$2a = (3 \times 6.24) + (8 \times 4.84) + (6 \times 4.87) + (4 \times 4.86) + 1.98 = 108.08$$

$$2b = (0.003 \times 3) + (0.00086 \times 8) + (0.00082 \times 6) + (0.00086 \times 4) = 0.02424$$

$$a = 54.04 \qquad b = 0.01212$$

$$t = \frac{-54.04 + \sqrt{(4000 \times 0.01212 \times 175.3) + (54.04 + 30 \times 0.01212)^2}}{2 \times 0.01212}$$

$$t = 2186° \text{ C.} \qquad T = 2459° \text{ absolute}$$

DETERMINATION OF PRESSURE

52. Pressure in a Closed Chamber.—We have examined the method of determining the potential of an explosive and the temperature of explosion. The pressure developed by an explosive on being fired in a closed chamber will now be considered. Two well-known laws of perfect gases are used as the basis for this determination.

Boyle's or Mariotte's Law.—At constant temperature the pressure of a given weight of gas varies inversely as its volume, or pv = constant.

Law of Charles or Gay-Lussac.—Under constant pressure, gases expand by a constant fraction of their volume at 0° C. for each degree rise in temperature. This fraction, or coefficient of expansion, is 1/273. In this discussion it is assumed that the gaseous products of an explosion are perfect gases, although this is not strictly correct. A kilogram is taken as the unit weight.

53. Characteristic Equation of Perfect Gases.—

Let p_0 = normal atmospheric pressure (a constant),

v_0 = the specific volume of the gas, i.e., the volume of a unit weight (1 kilogram) of the gas at 0° C. and atmospheric pressure (v_0 is therefore a constant),

v_t = the volume of a unit weight of gas at t° C. and atmospheric pressure,

p = any pressure to which the unit weight of gas may be subjected,

v = volume occupied by a unit weight of gas at t° C. and pressure p.

If p_0 and v_0 are the pressure and volume, respectively, of a unit weight of the gas at 0° C., then if the pressure remains constant and the temperature is changed to t° C., the new volume, v_t, in accordance with Gay-Lussac's law becomes

$$v_t = v_0\left(1 + \frac{t}{273}\right) \tag{12}$$

If this new volume, v_t, kept at constant temperature, is now subjected to a pressure p by which its volume is changed to v, we have according to Mariotte's law,

$$pv = p_0 v_t \tag{13}$$

Therefore,

$$v_t = \frac{pv}{p_0} \tag{14}$$

Substituting the value of v_t found in Eq. (12)

$$v_0\left(1 + \frac{t}{273}\right) = \frac{pv}{p_0} \tag{15}$$

or

$$pv = \frac{p_0 v_0}{273}(t + 273), \text{ for the gas at } t° \text{ C.} \tag{16}$$

If the same weight of gas is now at some other temperature, t', with a corresponding volume and pressure of v' and p',

$$\frac{p_0v_0}{273}(t' + 273) = p'v' \tag{17}$$

Combining Eqs. (16) and (17) above,

$$\frac{pv}{p'v'} = \frac{T}{T'} \tag{18}$$

where

$$T = t + 273$$

and

$$T' = t' + 273$$

that is, T and T' represent absolute temperatures.

Thus, if the pressure remains constant, the volume will vary as the absolute temperature; and if the volume remains constant, the pressure will vary as the absolute temperature.

If, merely as a matter of convenience, we let R represent the expression $p_0v_0/273$, which is constant for a given gas, Eq. (16) may be re-written in the form

$$pv = RT \tag{19}$$

This is called the characteristic equation of perfect gases and states that the product of the pressure and the volume of a *unit* weight of gas varies directly with the absolute temperature.

54. Application to Explosive Gases.—In order that Eq. (19) may be applicable to explosive and other actual gases, an experimental constant must be introduced into the equation which becomes

$$p(v - \alpha) = RT \tag{20}$$

where α is the co-volume of a unit weight of gas.

Application to Any Weight of Explosive.—Equation (19) has been deduced for a unit weight of perfect gas and Eq. (20) for a unit weight of explosive gas. If P and V represent any pressure and volume for any weight, $\bar{\omega}$, of explosive, Eqs. (19) and (20) may be expressed

$$PV = \bar{\omega}RT \tag{21}$$

$$P(V - \alpha\bar{\omega}) = \bar{\omega}RT$$

or

$$P = \bar{\omega}RT/(V - \alpha\bar{\omega}) \tag{22}$$

The Co-volume.—The constant α is known as the *co-volume* of the gas and has been defined as the smallest volume to which a *unit* weight of the gas can be compressed whatever the amount of pressure used.

Since, if an infinite pressure were applied, the molecules of the gas would be pressed together so as to be in contact, we may say that the co-volume is the actual incompressible volume of the molecules in a unit weight of gas. It is the limiting volume beyond which a unit weight of gas cannot be compressed. The expression $(v - \alpha)$ may be called the effective volume of the gas.

For powder gases, the co-volume, α, is generally taken as 1/1000 of the specific volume of the gas, that is, 1/1000 of the volume of a kilogram of the gas at 0° C. and atmospheric pressure, or

$$\alpha = \frac{V_k}{1000} \tag{23}$$

Pressure in a Powder Chamber.—The above conclusions provide a means of determining the pressure in a closed chamber where the explosive itself fills the entire volume. The method of determining pressures developed in the chamber of a gun, capable of variations in loading, will now be considered.

The *density of loading*, designated by Δ, must now be considered. It has been defined as the ratio between the weight of the powder charge and the weight of water which would fill the entire powder chamber. The term should not be confused with the specific gravity of the powder, δ.

If the weight of powder, $\hat{\omega}$, is given in kilograms and the volume of the powder chamber, S, is given in cubic decimeters,

$$\Delta = \frac{\hat{\omega}}{S} \quad \text{or} \quad S = \frac{\hat{\omega}}{\Delta}$$

since, numerically, the chamber volume in cubic decimeters is equal to the weight in kilograms of an equal volume of water.

Substituting this value of S for V in Eq. (22),

$$P = \Delta RT/(1 - \alpha\Delta) \tag{24}$$

which is an equation of first importance in the consideration of propellants and gives the maximum pressure to be expected in a firearm.

Solid Products of Explosion.—Some explosives, upon combustion, are not entirely converted into gas. Consider the reaction for black powder:

$$10KNO_3 + 3S + 8C = 3K_2SO_4 + 2K_2CO_3 + 6CO_2 + 5N_2$$

The potassium sulphate and potassium carbonate are solid products.

In such instances the solid products occupy space, and must be included in the co-volume. Equation (24) then becomes

$$P = \Delta RT/[1 - (\alpha + \alpha')\Delta]$$

in which α' represents the volume occupied by the solid products of a kilogram of the explosive.

EXAMPLES

55. Summary of Nitroglycerin Calculations.—The nitroglycerin reaction, in which all products are gaseous, will now be examined as a résumé of the foregoing work.

$$2C_3H_5(NO_3)_3 = 6CO_2 + 5H_2O + 3N_2 + \tfrac{1}{2}O_2$$

a. The total heat given off per gram molecule at constant pressure,

$$Q_{mp} = [(6 \times 94.39) + (5 \times 57.81) - 170.6]/2 = 342.4 \text{ large calories}$$

b. The total heat given off per kilogram at constant pressure,

$$Q_{kp} = 342.4 \times [1000/227.1] = 1507.7 \text{ large calories}$$

c. The total heat given off per gram molecule at constant volume,

$$Q_{mv} = Q_{mp} + 0.572n_m = 342.4 + (0.572 \times 7\tfrac{1}{4}) = 346.5 \text{ large calories}$$

d. The total heat given off per kilogram at constant volume,

$$Q_{kv} = 346.5 \times [1000/227.1] = 1525.8 \text{ large calories}$$

e. The number of volumes per gram molecule,

$$n_m = [6 + 5 + 3 + \tfrac{1}{2}]/2 = 7\tfrac{1}{4}$$

f. The number of volumes per kilogram,

$$n_k = 7\tfrac{1}{4} \times [1000/227.1] = 31.92 \text{ volumes}$$

g. The volume of the gas produced per gram molecule at 0° C.,

$$V_{m0} = 7\tfrac{1}{4} \times 22.4 = 162.4 \text{ liters}$$

h. The volume of gas produced per kilogram at 0° C.,

$$V_{k0} = 162.4 \times [1000/227.1] = 715.1 \text{ liters}$$

i. The volume of gas produced per kilogram at 15° C.,

$$V_{k15} = V_{m15} \times [1000/227.1] = 23.63 \times 7\tfrac{1}{4} \times [1000/227.1] = 754.4 \text{ liters}$$

j. The capacity for work or potential of one gram molecule at constant volume,

$$W_m = Q_{mv} \times 4270 = 346.5 \times 4270 = 1{,}479{,}555 \text{ kilogram decimeters}$$

k. The potential of one kilogram,

$$W_k = W_m \times 1000/227.1 = [1{,}479{,}555 \times 1000/227.1] = 6{,}514{,}993 \text{ kilogram decimeters}$$

l. The molecular specific heats of the gases in small calories at 0° C.,

$$a = [(6 \times 6.24) + (5 \times 6.58) + (3 \times 4.86) + (\tfrac{1}{2} \times 4.98)]/2 = 43.705$$

m. The increments of the mean molecular specific heat for each degree rise in temperature of the gaseous products of explosion,

$$b = [(6 \times 0.003) + (5 \times 0.0029) + (3 \times 0.00086) + (\tfrac{1}{2} \times 0.00086)]/2 = 0.01775$$

n. The temperature of the explosion from 0° C.,

$$t = \frac{-43.705 + \sqrt{(43.705 + 30 \times 0.01775)^2 + (4000 \times 0.01775 \times 346.5)}}{2 \times 0.01775} = 3360° \text{ C.}$$

$$T = 3360° + 273° = 3633° \text{ absolute}$$

o. The co-volume of the gases from one kilogram,

$$\alpha = (V_k/1000) = (715.1/1000) = 0.7151$$

p. The pressure produced by any amount of explosive in a closed chamber of any volume but with density of loading 0.5,

$$P = \Delta RT/[1 - \alpha\Delta]$$

$$P = \frac{0.5 \times \dfrac{103.33 \times 715.1}{273} \times 3633}{1 - 0.7151 \times 0.5}$$

$$= 765{,}291 \text{ kilograms per square decimeter}$$

56. Heat of Explosion of Propellants.—Propellants do not contain sufficient oxygen to convert all carbon and hydrogen present to carbon dioxide and water, and under gun-firing conditions sufficient atmospheric oxygen is not available in the gun to cause complete oxidation of the carbon and hydrogen. Therefore the heat effect of the explosion of a propellant in a gun or closed chamber is less than the heat of complete combustion. The heat effects and gaseous products under the two conditions are illustrated by the following example:

a. The explosion of a certain type of nitrocellulose powder may be represented by the following reaction:

$$\text{Molecular volumes} \rightarrow \quad 48 \quad + \quad 48 \quad + \quad 20 \quad + \quad 39 \quad + 21 = 176$$

$$2C_{48}H_{59}N_{21}O_{82} = 48CO + 48CO_2 + 20H_2O + 39H_2 + 21N_2$$

Heats of formation → 1269 + 4531 + 1156 = 6956 L. C. for 2 gram molecules (4484 grams). Per kilogram of the powder, the aggregate of the heats of formation of the products of explosion, at 15° C. and atmospheric pressure, is $\frac{6956 \times 1000}{4484} = 1551$ L. C.

b. If the necessary additional oxygen were supplied, complete combustion would take place as follows:

$$\text{Molecular volumes} \rightarrow \quad 96 \quad + \quad 59 \quad + 21 = 176$$

$$2C_{48}H_{59}N_{21}O_{82} + 43.5\,O_2 = 96CO_2 + 59H_2O + 21N_2$$

$$\text{Heats of formation} \rightarrow \quad 9061 \quad + \quad 3411 \quad = 12{,}472 \text{ L. C.}$$

Therefore, per kilogram of explosive, the aggregate of the heats of formation of the products of complete combustion is $\frac{12472 \times 1000}{4484} = 2781$ L. C.

Comparison.—It is apparent that the volume of the resulting gases is the same in both cases, being 176 molecular volumes from 2 gram molecules of the explosive, but that the heat of explosion is much less in incomplete combustion. If the heat of formation of 1 kilogram of the explosive is 569 L. C., the resulting values of Q_{kp} are

$$1551 - 569 = 982 \text{ L. C. for explosion}$$

$$2781 - 569 = 2212 \text{ L. C. for complete combustion}$$

Although the volume of the gases is the same in each case, the temperature of explosion and the pressure in a closed chamber would be greater in complete combustion because of the greater amount of heat given off in the reaction.

57. Comparison of FNH and NC Propellants.—The standard nitrocellulose powder for the 75-mm. gun has the following composition:

Nitrocellulose (12.60% N)	96.5%
Volatiles	3.0%
Diphenylamine	0.5%

The FNH powder discussed in Section 7, Chapter I, has the following composition:

Nitrocellulose (12.60% N)	74%
Nitrocellulose (13.25% N)	20%
Dinitrotoluene	5%
Diphenylamine	1%

The heat effects and gaseous products resulting from explosion of one kilogram of these propellants in a closed chamber, as determined by calorific and analytical data, are as follows:

Per Kilogram	NC	FNH
Heat of explosion	896 L. C.	786 L. C.
Volume of gaseous products (at atmospheric temperature)	791 liters	839 liters

Because of the lower heat energy of the FNH powder, the gases emerging from the muzzle will be cooler than for the NC powder and, with proper granulation, muzzle flash will be eliminated or greatly reduced.

The heat of explosion from one kilogram of a powder containing 80 per cent nitrocellulose and 20 per cent nitroglycerin is approximately 1065 L. C., which exceeds that of straight nitrocellulose powder by 169 L. C. per kilogram. It is apparent that an increased amount of cooling agents would have to be added to nitrocellulose-nitroglycerin powders to produce flashlessness, and this may be impracticable owing to the resulting increase in smoke.

CHAPTER III

INTERIOR BALLISTICS

58. Definition and Scope.—Ballistics is the science that treats of the motion of projectiles, and is a particular branch of applied mechanics. Interior ballistics treats of the motion of the projectile while still in the bore of the gun and exterior ballistics treats of the motion of the projectile after it leaves the muzzle.

Interior ballistics includes a study of the mode of combustion of the powder, the pressure developed, the velocity of the projectile along the bore, and the calculation of the dimensions of the powder chamber and of the powder which, for any particular design of gun and projectile, will give the required muzzle velocity while not exceeding the permissible

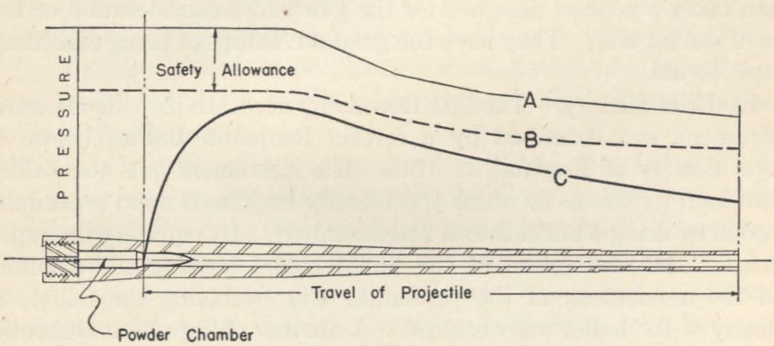

FIG. 15.

interior pressure. Having determined the powder-pressure curve for the gun, the thickness of wall of the gun to withstand the expected pressure at each point may be determined by the principles of gun construction.

The strength of a gun is fixed by its design, the study of which will be taken up in a subsequent chapter. The greatest interior pressure which it may withstand without exceeding the elastic limit of the metal is known as the *elastic strength pressure*. This value varies along the bore as indicated by Curve A of Fig. 15. After making an allowance for safety, a curve of *permissible pressure* is established as shown by Curve B.

The values shown by this curve must not be exceeded at any point along the bore and, in practice, actual pressures will generally lie below this curve about as indicated by Curve *C*.

Interior ballistics is not an exact science. Many formulas and equations have been developed for the expression of projectile velocities and powder pressures as functions of time or distance traveled by the projectile along the bore. The development of any of the known formulas requires certain assumptions to reduce them to usable form. Some of these assumptions approximate the truth only when a powder or gun of certain characteristics is used. Present standard practice in our service involves the use of prepared "Tables for Interior Ballistics,"* based on the integration of three fundamental differential equations relating to energy of the charge, motion of the projectile, and rate of burning of the powder. The development and integration of these equations, and the use of the tables, are beyond the scope of this text.

The formulas to be used in this study are those developed by a French artillerist, Captain A. Le Duc. The Le Duc formulas do not give the accuracy of the equations just referred to, but they are sufficiently trustworthy to give approximations of velocities and pressures to be expected when using a powder designed for the gun under consideration or for a gun of similar size. They have the great advantage of being exceedingly simple to use.

59. Brief History.—The first reasonably accurate ballistic measuring instrument was described by a certain Benjamin Robins before the Royal Society of England, in 1743. His instrument was the ballistic pendulum, by means of which the velocity impressed upon a pendulum of wood by firing a bullet into it was measured. By equating the expressions for the momentum of the bullet before striking the pendulum and the momentum of the pendulum after receiving the bullet, the velocity of the bullet was obtained. A number of important theoretical conclusions were reached by Robins in his investigations.

Further experiments with the ballistic pendulum, extending to 1791, were conducted by Dr. Charles Hutton. Hutton produced a formula for the velocity of a spherical projectile at any point of the bore, upon the assumption that the combustion of the charge is instantaneous and that the expansion of the gas follows Mariotte's law, no account being taken of the loss of heat due to the work performed.

No major experiments were made in the United States until 1857, when General Rodman conducted the investigations that resulted in a complete change in the form of powder grains and their variation in

* (Ordnance Department Document No. 2039.)

size according to the caliber of the gun. He originated "progressive burning" and devised the pressure gage for directly measuring the maximum pressures of powder gases in guns. General Rodman's experiments also led to his discovery of the principle of interior cooling of cast-iron cannon, by the application of which principle the metal surrounding the bore of a gun was put under a permanent compressive strain which greatly increased the resistance of the gun to interior pressures.

In 1874 the British experimenters, Noble and Abel, announced the results of their experiments on the explosion of gunpowder in closed vessels. Their analyses of powder gases and their conclusions were generally accepted by the scientific world and were far-reaching in encouraging further experimentation.

In 1875 Emile Sarrau, engineer in chief of the French powder factories, after exhaustive mathematical and experimental research following the work of General Rodman, proposed his mathematical formulas connecting the travel, velocity, and pressure in the bore of a gun when geometrically grained black powders were used. His formulas gave results which were closely confirmed by experimental firings.

Theoretical investigations by Resal preceded those of Sarrau, and the important energy equation of interior ballistics is named after him.

The success of Vieille in producing a smokeless powder by colloiding nitrocellulose was of far reaching importance. This success has been mentioned in Chapter I.

With the adoption of smokeless powders, it was found that the formulas of Sarrau were not suitable and many investigators have undertaken the task of revising them or of developing new ones. Among these investigators may be mentioned Gossot, Liouville, Hugoniot, Charbonnier, Le Duc, and Muraour of France; Cranz, Poppenberg, and Schmidt of Germany; Love and Pidduck, Crowe and Grimshaw, and Petavel of England; Roggla of Czecho-Slovakia; Ingalls, Tschappat, and Bennett of the United States.

60. Distribution of Energy of Powder Gas.—The energy given off when the powder charge is burned in the gun is distributed as follows:

(*a*) Energy of translation of the projectile.

(*b*) Energy of rotation of the projectile.

(*c*) Energy of translation of the gun (recoil).

(*d*) Energy of translation of the unburned charge and gases. The total weight of the unburned charge and gases is always that of the original charge, and it is assumed as uniformly distributed between the face of the breechblock and the base of the projectile.

(*e*) Energy consumed in overcoming the passive resistance of the projectile. This resistance arises from the friction of the projectile against the walls of the bore and of the rotating band against the driving edges of the lands. In the first stages it also arises from the cutting of grooves in the rotating band by the lands. In rifling with increasing twist a resistance is caused by the change in pitch of these grooves as the projectile moves through the bore.

(*f*) Energy lost as heat to the gun.

(*g*) Energy that remains in the gas as sensible heat and as latent heat.

61. Ignition.—The basic requirements of an ignition system have already been discussed in Chapter I. Although it is not practicable to design a system which would insure the simultaneous ignition of all grain surfaces throughout the charge, it is possible to obtain a system which will function with sufficient efficiency, and uniformity from round to round, that the burning of the charge will result in correspondingly uniform pressures and velocities, within the limits desired. The combination of primer, igniter, form and size of powder grain, and type of charge which will produce the best results with a given combination of gun and projectile can be determined only by experiment. In recent years, ignition problems have been carefully studied and considerable progress towards the attainment of consistently uniform pressures and velocities has resulted from ignition improvements.

In fixed ammunition the igniting charge of black powder becomes a part of the primer, and is made as large as necessary to accomplish its purpose. The body of the primer is so constructed, and of such length, that the hot gases from the burning black powder are distributed effectively throughout the propelling charge. The charge should be located from round to round in the same position relative to the primer. In some recent types of fixed ammunition where the charge does not entirely fill the cartridge case, this correct positioning is obtained by use of wadding to fill the forward part of the case not occupied by the charge.

In separate-loading ammunition, where powder and projectile are entirely separate, the powder charge is placed in one or more cloth bags. Under such conditions, an ignition charge of black powder must be inserted in the smokeless powder charge to secure proper ignition. Sometimes the ignition charge is simply a pad of black powder sewed into each end of the powder bags; and sometimes a thin bag of black powder is run longitudinally through the center of the charge. In the single-section charge, which consists of one long powder bag containing the entire charge, the igniter is a long core of black powder running from

the rear end to the front end of the powder bag. To obtain uniformity of ignition, of burning of the charge, and of pressures and velocities, not only must the charge itself be uniform in weight, composition, and dimensions from round to round, but there must also be correct and uniform loading methods employed at the gun. Variations of the position of the charge between the primer and the projectile, and in diametrical clearance within the powder chamber, result in variations of ignition and burning of the charge.

62. Granulation.—Smokeless powders are granulated in regular geometrical forms of various sizes and lengths as illustrated in Fig. 16. The principal forms in use are the solid cord of considerable length used in English cordite, the flat strip, the single perforated cylinder, and the multiperforated cylinder.

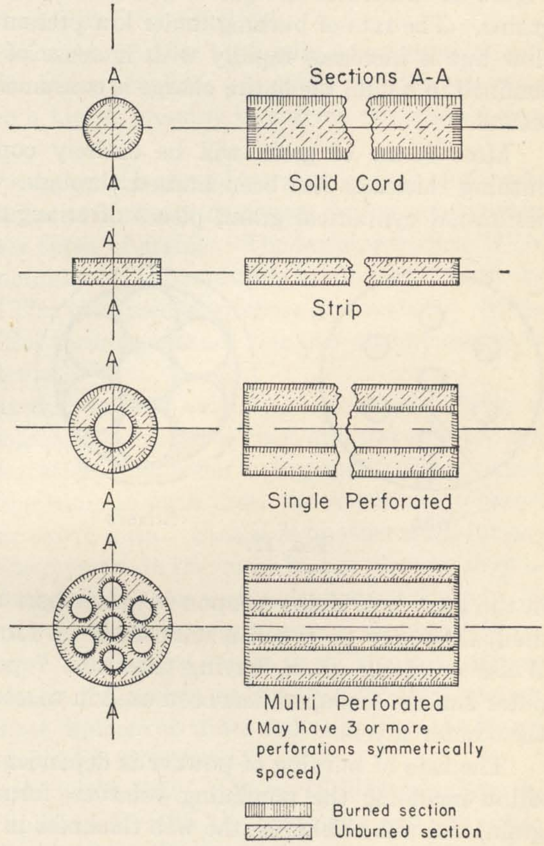

FIG. 16.

The cylindrical grain of seven perforations has been adopted as the standard for American cannon powders. With this grain, relatively high velocities and low maximum pressures are obtainable owing to its increasing burning surface; and, when of proper size for the gun and projectile, this grain gives good uniformity of velocities and pressures.

The single perforated grain is used for small arms and certain minor caliber powders because of the impracticability of manufacturing a multiperforated grain of the required dimensions. Strip powder may be used as a substitute cannon powder to augment production during an emergency.

The most important dimension of a powder grain is the *web thickness*, which is the minimum burning thickness or the minimum thickness of the grain between any two boundary surfaces. For any given geometrical form the web thickness is dependent upon the size of the grain.

63. Mode and Rate of Burning.—Each grain of smokeless powder burns in parallel layers in directions perpendicular to all ignited surfaces. Figure 16 illustrates the partially burned condition of several types of grains. The rate of burning under low pressures, as in the air, is quite slow but it increases rapidly with increase of pressure until, as when confined in a gun, the entire charge is consumed in a small fraction of a second.

Most forms of grain will be entirely consumed when the least-burning thickness has been burned through. However, in the multi-perforated cylindrical grain, pieces of triangular cross section termed *slivers* remain unburned when the web thickness has been burned through. In the standard 7-perforation type, 12 of these slivers remain, aggregating about 15 per cent of the total weight. (See Fig. 17.) Usually, the slivers are consumed while the projectile is still in the gun, but, if the weapon is quite short or if a reduced charge is used, they may be expelled unburned. A form of grain known as the *Walsh* or *rosette* grain, having the usual 7 perforations but with the outer surface scalloped, has been used in seacoast mortars to eliminate the 6 outer slivers.

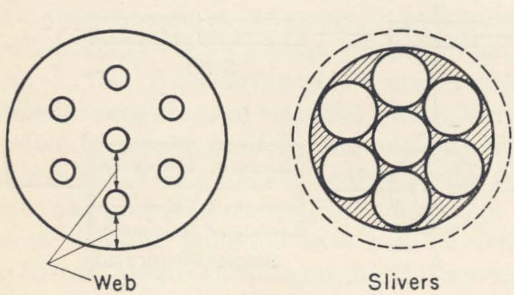

FIG. 17.

The rate of burning of powder is dependent upon nitration, composition including the remaining volatiles, form and dimensions of the grain, and web thickness; the web thickness in a standard form of grain varies with the size. The practice is to keep the composition and shape of grain uniform, to specify within narrow limits the moisture and volatile content for each grain size, and to obtain variations in burning rate to satisfy requirements of a given gun and projectile combination by varying the size of grain.

Accordingly, since powder burns only on its exposed surfaces, the rate of gas evolution will depend upon the area of the burning surface. For a given weight of powder the initial burning surface will depend upon the form and dimensions of the grains. As burning continues,

the rates of combustion and of pressure variation will depend upon how the area of surface changes, that is, upon the rate of area increase or decrease.

A law of burning proposed by Muraour seems to fit the facts very well. According to this law the rate of regression of the burning surface is equal to $k + k_1P$, where k and k_1 are constants and P is the pressure. There is evidence to indicate that k expresses the effect of radiation on the heat transfer, and k_1P the effect of conduction.

The *quickness* of a powder is a relative term only, expressing its rate of burning compared with other powders. A quick powder will burn more rapidly and produce a higher pressure in a given gun than a slow powder.

From Fig. 16 we may see that the area of burning surface of all solid grains, such as cord or strip, continually decreases during combustion. These are termed *degressive* types of grains. The burning surface of the multiperforated grains actually increases during combustion until the web is burned through. This is termed *progressive* granulation. In the single-perforated grains the burning surface remains almost constant, being very slightly degressive.

In developing any desired muzzle velocity, a degressive form of powder will produce its maximum pressure earlier, and the pressure will decrease more rapidly thereafter, than when a progressive form is used. Since the work done is the same in each case, the maximum pressure must be higher for the degressive form. Stated in another way, for any given maximum permissible pressure in the gun a higher velocity may be obtained with a progressive powder than with a degressive powder. It must be understood that the foregoing is only a general discussion of the shape of the pressure curves. The actual values in each powder depend upon the dimensions of the grains, and in no instance should a weapon be fired with a powder whose dimensions differ radically from the standard for the weapon and projectile concerned.

64. Considerations as to Grain Size.—Figure 18 illustrates the use of powders of different "quickness" with the same gun and projectile, producing the same muzzle velocity. Curve A represents the effect of an instantaneous powder, were it possible to obtain such a powder. It is purely hypothetical, starting with a very high maximum pressure and decreasing in a manner similar to the standard adiabatic expansion.

Curve B represents the effect of a relatively fast progressive powder. Curve C shows the action of a progressive powder slower than that indicated by curve B. Curve D represents a still slower progressive powder. Since each of these four powders is assumed to produce the same muzzle velocity, the area under each of the curves must be equal.

Although each of these four powders produces the same velocity, the maximum permissible pressure of the gun would certainly be exceeded by the instantaneous powder, and probably by powder "B." Assuming that powder "C" did not exceed the permissible pressure, then either "C" or "D" might be used. Of these powders, "C" is more desirable for reasons to be brought out later.

If it is desired to obtain a higher velocity with this same gun and projectile than is possible with "C," we might do so by using powder "D" with an increased weight of charge, bringing the maximum pres-

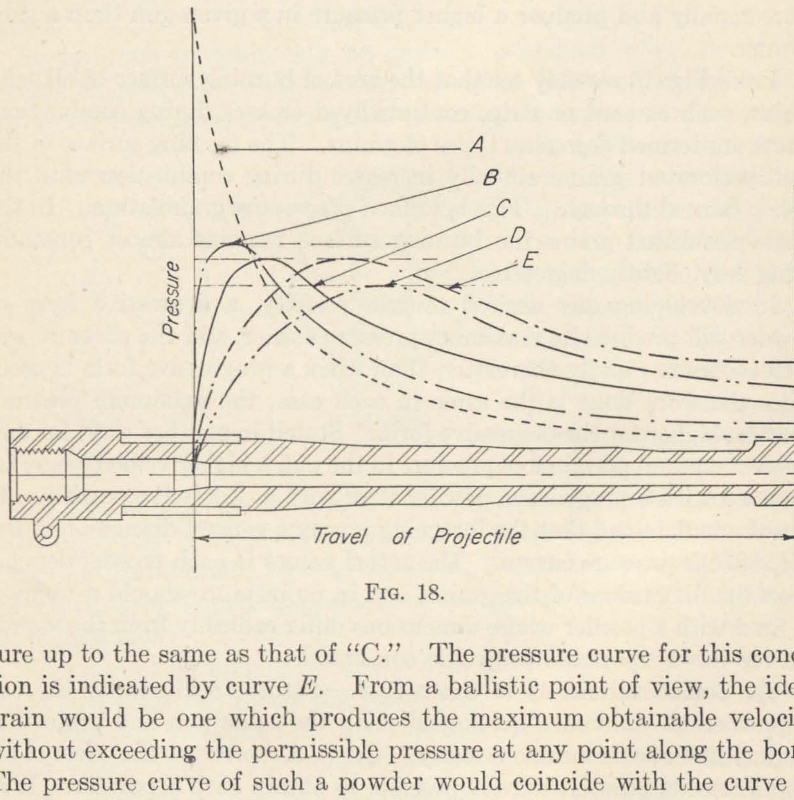

FIG. 18.

sure up to the same as that of "C." The pressure curve for this condition is indicated by curve E. From a ballistic point of view, the ideal grain would be one which produces the maximum obtainable velocity without exceeding the permissible pressure at any point along the bore. The pressure curve of such a powder would coincide with the curve of permissible pressure in the gun. (Fig. 15.) Even if such a grain were possible of design and manufacture, it would have such serious practical objections as excessive erosion, brilliant flash, non-uniformity of velocity and pressure, and would require an excessively large volume in the powder chamber with a corresponding increase in weight along the breech section of the gun.

In selecting a suitable granulation, the questions of erosion, flash,

and uniformity must be considered. Erosion increases with weight of charge, velocity, and temperature, and it is not possible to obtain the maximum energy from a gun without seriously reducing its accuracy life. High muzzle pressure increases flash and reduces uniformity of velocity. From a practical consideration, therefore, the prescribed velocity is somewhat below the maximum obtainable and the best grain is that which will give uniformly the prescribed velocity without exceeding the permissible pressure at any point. Such a grain is somewhat faster (of smaller web) than the ideal, and the charge is of smaller size and weight.

INTERIOR BALLISTIC FORMULAS

The symbols used in the interior ballistic formulas and their significance are listed below for easy reference.

$\left.\begin{matrix} a \\ b \end{matrix}\right\}$ = constants whose value depends upon the powder, gun, and projectile.

A = area of the cross section of the bore, or of the projectile, in square inches.

β = powder constant, a numerical value assigned to each lot of powder to indicate its "quickness" or rate of burning under standard conditions. It is dependent upon the composition, form, and dimensions of the grains, and varies inversely with the burning rate.

δ = specific gravity of the powder, usually between 1.54 and 1.62.

Δ = density of loading, equals ratio between the weight of the charge and the weight of water required to fill the powder chamber. Since 1 lb. of water occupies 27.68 cu. in.,

$$\Delta = \frac{27.68\,\hat{\omega}}{S} \tag{1}$$

g = acceleration of gravity, taken as 32.2 ft. per second per second.

P = actual or computed pressure of the powder gases at any point in the bore, in pounds per sq. in.

P' = maximum value of P.

P_v = that part of the pressure at any point in the bore *producing velocity only.*

P'_v = maximum value of P_v.

S = volume of powder chamber, in cubic inches. It includes the entire space between the seated projectile and the closed breechblock. In fixed ammunition it is the volume of the cartridge case behind the projectile.

u = travel of the projectile to any point in the bore, in feet.

U = total travel of the projectile in the bore, or distance from the origin of rifling to the muzzle, in feet. At the muzzle $u = U$.

v = velocity of the projectile at any point in the bore, in feet per second.

V = muzzle velocity, in feet per second. At the muzzle $v = V$.

w = weight of the projectile, in pounds.

$\hat{\omega}$ = weight of the smokeless powder in the charge, in pounds.

The *initial air space* is that volume of the powder chamber which is not occupied by the solid powder. The volume of solid powder equals $\frac{27.68\,\hat{\omega}}{\delta}$, which equals $\frac{S\Delta}{\delta}$; hence the initial air space equals $S - \frac{S\Delta}{\delta}$.

65. The Le Duc Equation for Velocity.—After a long consideration of the subject and a study of all the experimental work available, Le Duc assumed that a hyperbolic curve, whose general equation takes the form $y = \frac{ax}{b + x}$, would represent the velocity-travel relation of a projectile while in the bore of the gun; where y represents velocity and x travel of the projectile. The graph passes through the origin, rises rapidly, and then flattens out. The velocity is zero when travel along the bore is zero, it increases very rapidly as the projectile proceeds along the bore, and then the effect of prolonging the bore becomes less and less.

Le Duc wrote his equation as follows:

$$v = \frac{au}{b + u} \tag{2}$$

where v is the velocity of the projectile, in feet per second.

u is the travel of the projectile in the bore, in feet, corresponding to v.

a and b are constants to be determined.

For muzzle conditions where $u = U$ and $v = V$, this equation may be written

$$V = \frac{aU}{b + U}$$

This hyperbolic curve is a fair approximation of the velocity-travel relation but it should be remembered that it is not always accurate.

Determination of "a."—Suppose the length of the gun to be indefinitely prolonged so that the powder gases may expand without limit. u becomes infinitely large and $u/(b + u)$ approaches unity. Then

$v = a$; and a is the theoretical value of the velocity of the projectile attained in a gun of infinite length.

The kinetic energy of the projectile at any time is $\frac{1}{2}(w/g)v^2$, where w is the weight of the projectile in pounds. Under the condition that $v = a$, this energy is $\frac{1}{2}(w/g)a^2$.

An expression for this total energy of the powder can also be found by assuming infinite expansion of the gases resulting from explosion. An expression representing the potential of the expanding gases equated to $\frac{1}{2}(w/g)a^2$ will give an equation from which a value of a may be determined.

From the results of various methods of calculation modified by the results of experimental firings, it was determined that

$$a = 6823(\bar{\omega}/w)^{1/2}\Delta^{1/12} \tag{3}$$

in which $\bar{\omega}$ represents the weight of the charge in pounds and Δ represents the density of loading. This formula is accepted and used in all calculations by the Le Duc equations.

Determination of "b."—The acceleration of the projectile at any point in its travel is given by the first derivative of the velocity,

$$dv/dt = d^2u/dt^2$$

The total force imparting velocity to the projectile is given by the relation

$$\text{Force} = \text{mass} \times \text{acceleration}$$

$$= \frac{w}{g}\left(\frac{dv}{dt}\right) \tag{4}$$

The unit force or unit pressure acting on the base of the projectile to produce velocity, is then

$$P_v = \frac{w}{Ag}\frac{(dv)}{(dt)} \tag{5}$$

where P_v is pressure in pounds per square inch, and A is the area of the base of the projectile, in square inches.

From Eq. (2),

$$\frac{dv}{dt} = \frac{(b+u)\,a\dfrac{du}{dt} - au\dfrac{du}{dt}}{(b+u)^2} \tag{6}$$

$$= \left[\frac{ab}{(b+u)^2}\right]\frac{du}{dt} \tag{7}$$

But

$$du/dt = v = au/(b + u) \tag{2}$$

Therefore

$$\frac{dv}{dt} = \frac{ab}{(b + u)^2} \times \frac{au}{b + u} = \frac{a^2bu}{(b + u)^3} \tag{8}$$

Since the powder pressure curve follows the acceleration curve of the projectile, the pressure will be a maximum when the acceleration is a maximum; that is, when $d^2v/dt^2 = 0$. But from Eq. (8),

$$\frac{d^2v}{dt^2} = \frac{d}{dt}\left[\frac{a^2bu}{(b + u)^3}\right] \tag{9}$$

$$= \frac{(b + u)^3a^2b - 3a^2bu(b + u)^2}{(b + u)^6}\frac{du}{dt} \tag{10}$$

$$= \frac{(b + u)a^2b - 3a^2bu}{(b + u)^4}\frac{du}{dt}$$

$$= (b - 2u)\frac{a^2b}{(b + u)^4}\frac{du}{dt} \tag{11}$$

When $d^2v/dt^2 = 0$

$$(b - 2u) = 0 \tag{12}$$

and

$$u = \frac{b}{2} \textit{ when the pressure is a maximum} \tag{13}$$

Therefore, the constant "b" is equal to twice the travel of the projectile to the point of maximum pressure.

General Formula for "b."—The distance the projectile travels before the maximum pressure is reached depends directly upon the *initial air space* and upon the powder constant. It also varies inversely with some power of the chamber volume and the weight of the projectile. Accordingly, an empirical formula for b may be stated as follows:

$$b = \frac{\beta\left(S - \frac{S\Delta}{\delta}\right)}{S^z \times w^y} \tag{14}$$

where z and y represent some undetermined power of S and w.

For convenience, assume $S/S^z = S^x$.

Then, from Eq. (14),

$$b = \frac{\beta\left(1 - \frac{\Delta}{\delta}\right)S^x}{w^y} \tag{15}$$

It has been determined by experiments that both x and y in the foregoing equation have the approximate value two-thirds.

Hence,

$$b = \beta\left(1 - \frac{\Delta}{\delta}\right)(S/w)^{2/3} \tag{16}$$

This formula for b is the one used in all calculations by the Le Duc method.

66. Determination of Velocity.—From Eqs. (3) and (16) definite values for a and b can be determined for a particular gun firing a projectile of weight w and a powder having a known powder constant, β.

From the equation

$$v = \frac{au}{b + u} \tag{2}$$

the velocity for any assumed travel may be obtained.

67. Determination of Pressure.—The pressure, P_v, imparting velocity to the projectile, may be determined for any point along the bore from Eqs. (5) and (8).

$$P_v = \frac{wa^2bu}{gA(b + u)^3} \tag{17}$$

Since, at the time of maximum pressure, $u = \frac{b}{2}$, we may substitute the value of u in Eq. (17) and obtain an expression for the maximum value of P_v:

$$P'_v = \frac{4wa^2}{27gAb} \tag{18}$$

where P'_v is the *maximum pressure producing velocity only.*

Since there must also be pressure to overcome friction, force the rotating band through the rifling, impart rotation to the projectile, etc., the actual pressure in the bore is greater than the pressure producing velocity alone. The actual bore pressures, which have been found to be approximately 1.12 times the pressure producing velocity alone, are given by the formulas

$$P = \frac{1.12wa^2bu}{gA(b + u)^3} \tag{19}$$

$$P' = \frac{4.48wa^2}{27gAb} \tag{20}$$

for any point in the bore, and at point of maximum pressure, respectively.

Practically, the pressures in the gun are measured by gages, as will be explained later.

68. Application of Formulas.—To illustrate the use of the Le Duc formulas, a problem will be given showing the manner in which these interior ballistic principles may be applied in the adaptation for use in a 4.7-in. field gun of an existing powder manufactured for a 3-in. field gun.

Solution for 3-in. Field Gun.—From the ballistic tests of the powder, it was found that a charge of 1.355 lb. gave a muzzle velocity of 1700 ft. per sec. in the 3-in. Field Gun, Model 1905, with a 14.98-lb. standard shell. The charge of this same powder required to give a velocity of 1250 ft. per sec. in the 4.7-in. Field Gun, Model 1906, with a 45-lb. projectile is calculated in the following manner:

For the 3-in. field gun, these quantities are known:

$$V = 1700 \text{ ft. per second.}$$
$$U = 6.21 \text{ ft.}$$
$$S = 66.5 \text{ cu. in.}$$
$$w = 14.98 \text{ lb.}$$
$$\hat{\omega} = 1.355 \text{ lb.}$$
$$\delta = 1.618.$$

From Eq. (1), $\Delta = 27.68 \times 1.355/66.5 = 0.564$

From Eq. (3), $a = 6823[1.355/14.98]^{1/2}(0.564)^{1/12} = 1956$

From Eq. (2), $1700 = 1956 \times 6.21/(b + 6.21)$

$$\therefore b = 0.9353$$

From Eq. (16), $0.9353 = \beta\left(1 - \dfrac{0.564}{1.618}\right)\left[\dfrac{66.5}{14.98}\right]^{2/3}$

$$\therefore \beta = 0.5315$$

The powder constant, β, and the specific gravity, δ, are the only factors pertaining to the powder alone *and hold for both guns.*

Solution for 4.7-in. Field Gun.—For the 4.7-in. gun, the following quantities are known:

$$\beta = 0.5315.$$
$$V = 1250 \text{ ft. per second.}$$
$$U = 9.59 \text{ ft.}$$
$$S = 251 \text{ cu. in.}$$
$$w = 45 \text{ lb.}$$
$$\delta = 1.618.$$

It is now necessary to compute for the 4.7-in. gun the values of the four unknown quantities, a, b, Δ, and $\hat{\omega}$.

From Eq. (3), $a = 6823\left(\dfrac{\hat{\omega}}{45}\right)^{1/2}\Delta^{1/12}$

From Eq. (1), $\hat{\omega} = \dfrac{251\Delta}{27.68}$

giving

$$a = 6823\left(\frac{251\Delta}{(27.68 \times 45)}\right)^{1/2}\Delta^{1/12} \tag{21}$$

$$\therefore a = 3063\Delta^{7/12}.$$

From Eq. (16), $b = 0.5315\left(1 - \dfrac{\Delta}{1.618}\right)\left(\dfrac{251}{45}\right)^{2/3}$

$$= 1.031(1.618 - \Delta) \tag{22}$$

Substituting in Eq. (2) the values of a, b, v, and u for the 4.7-in. gun gives

$$14074 - 1268\Delta = 29370\Delta^{7/12} \tag{23}$$

Here is an equation involving Δ and $\Delta^{7/12}$, which must be solved for Δ. As the algebraic solution is complicated, a graphical solution may be used.

Assume $$y = 14074 - 1268\Delta \tag{24}$$

and $$y = 29370\Delta^{7/12} \tag{25}$$

The right-hand members of these equations are the left-hand and right-hand members of Eq. (23). By assigning convenient values to Δ, curves of the two equations can be constructed. The point of intersection of these curves is, then, that value of Δ which satisfies both equations, or both members of Eq. (23). Therefore, it is the value of Δ in Eq. (23).

The following tabulations show the values of y for the corresponding values of Δ in Eqs. (24) and (25), respectively:

Δ	y
0	14074
0.5	13440

Δ	y
0	0
0.1	7667
0.2	11480
0.3	14550
0.4	17210
0.5	19600
0.6	21800

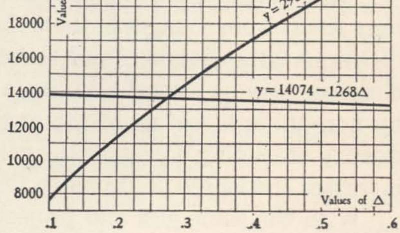

FIG. 19

Plotting these two graphs, as shown in Fig. 19, it is seen that they

intersect at the point where $\Delta = 0.272$. This then is the value of Δ and, by substitution in Eq. (1),

$$\hat{\omega} = \frac{251 \times 0.272}{27.68}$$

$$= 2.46 \text{ lb.}$$

This is the charge of the 3-in. gun powder that should produce a velocity of 1250 ft. per second in the 4.7-in. gun.

The values for a and b for this charge in the 4.7-in. gun, found by substituting in Eqs. (21) and (22), are

$$a = 1432$$

$$b = 1.389$$

Substituting these values in the equation for maximum bore or gage pressure gives $P' = 19{,}800$ lb. per sq. in.

EFFECT OF VARIATIONS FROM STANDARD CONDITIONS

69. Change in Length of Bore.—If the length of the bore of the 4.7-in. gun previously considered be increased 2 in., then

$$U = 9.76 \text{ ft.}$$

The values of a and b remain the same and

$$V = 1253 \text{ ft. per second}$$

instead of 1250 ft. per sec.

If it be desired to obtain a muzzle velocity of 1260 ft. per second by increasing the length of the bore, it will be found from Eq. (2) that $U = 10.18$ ft., or 7.1 in. must be added.

In either case, the maximum pressure would remain the same since it is independent of changes in u beyond the point of maximum pressure.

70. Change in Density of Loading.—A change in density of loading may result from changes in the weight of charge or changes in the volume of the powder chamber, and the changes in the volume of the powder chamber may be caused by using a different type of gun or projectile, or by non-uniform seating of the projectile. In general, a decrease in the density of loading decreases the velocity and the maximum pressure, but increases the length of travel to the point of maximum pressure.

With the same gun and projectile, a change in density of loading is obtained only by changing the weight of powder charge, or by non-uniform seating of the projectile. In either of these instances, for small changes, the approximate rule is: *The velocity varies as the square root of*

the density of loading. This is only approximate, as may be observed from an inspection of Eqs. (1), (2), and (3). An increase in Δ of 1 per cent in the loading of the 4.7-inch gun changes the velocity from 1250 to 1258 ft. per sec.

With very small values of densities of loading there is considerable variation in muzzle velocity, due probably to non-uniform ignition, and the fact that portions of the charge may be hurled against the base of the projectile and broken up. There sometimes results pressure surges or "waves" of considerable intensity. As the density of loading is increased, a critical value is approached beyond which even a slight increase causes a great increase in pressure. For this reason, in testing a new powder it is necessary to start with a smaller weight of charge than calculated, and to increase the weight by small increments until the desired velocity is obtained or until the maximum permissible pressure is reached.

71. Change in Weight of Projectile.—A change in the weight of the projectile, other elements remaining the same, affects both the constants a and b as is evident from an inspection of Eqs. (3) and (16). But as a is a factor and b is an additive term in Eq. (2), a has the greater influence.

The approximate rule is: *The velocity varies inversely as the square root of the weight of the projectile.*

72. Erosion in the Bore.—The accuracy life of a gun depends upon the condition of its bore. Erosion and corrosion determine this condition. Erosion is the result of firing; corrosion is the result of neglect.

Erosion is the breaking down and wearing away of the metal at the surface of the bore. The area of greatest erosion is immediately in front of the powder chamber of the gun, where the temperature of the powder gases is greatest. Erosion results in the tearing away of the lands and makes a rough and enlarged bore with a consequent reduction in pressure and velocity. Excessive erosion causes the gun to lose its ability to rotate the projectile, which consequently tumbles and becomes inaccurate in flight.

The complete explanation of erosion is somewhat in doubt, but evidence indicates that the following are probably the principal causes:

(*a*) A thin film of metal along the surface of the bore is melted and carried away by the hot gases moving at high velocity.

(*b*) Mechanical abrasion by the projectile, gas, and solid portion of the partially burned charge.

(*c*) Nitrogen or carbon, or both, may be absorbed by the steel of the bore surface, forming a very brittle compound which is easily broken and worn away under the action of the powder gases.

The reduction in pressure and velocity is due to the leakage of gas past the rotating band while in the eroded section of the bore, and to the fact that the projectile moves forward from its seat in the bore before the normal pressure has been reached. This latter condition increases the air space, changes the rate of travel of the projectile along the bore, and decreases the efficiency of the powder.

It may be assumed that the accuracy life of a 14-in. gun is approximately 250 rounds. Erosion curves based on proving-ground tests are sometimes plotted to indicate the falling off in velocity and pressure in accordance with the erosion resulting from the number of rounds fired. From such curves approximate corrections in range may be obtained for the gun.

A major caliber gun which has worn out is sent to an arsenal for relining, and this again gives it the ballistics of a new weapon. There appears to be almost no limit to the number of relinings, one 14-in. gun having been successfully relined fourteen times.

73. Effect of Variations in Powder Composition.—As pointed out in Section 18, a definite residual moisture and volatile content is specified for each powder composition and granulation. Powder may also contain small percentages of some stabilizer (such as diphenylamine), graphite, and inert materials. All these ingredients affect the energy of the powder, and any changes will cause ballistic variations. The only variations in composition likely to result in service are those involving loss of volatiles and change in moisture content.

Calculations show that the energy per pound of pure nitrocellulose of 12.60 per cent nitrogen is about 1,425,000 ft-lb. If an inert material, that is, one which takes no part in the reaction on explosion, is mixed with the nitrocellulose, the energy per pound of the resulting material will be less than that of the pure nitrocellulose. For instance, if 0.99 lb. of pure nitrocellulose of 12.60 per cent nitrogen is mixed with 0.01 lb. of inert material, the inert material will be 1 per cent of the total weight and the energy per pound of the resulting material will be $1{,}425{,}000 \times 0.99 = 1{,}410{,}000$ ft-lb.

Moisture in powder is considered as having the same effect as the same percentage of inert material. Alcohol (C_2H_5OH) has a greater effect in decreasing the energy than the same amount of inert material. The carbon of the alcohol combines with the CO_2 resulting from the combustion of the nitrocellulose, thus forming a larger quantity of CO and a smaller quantity of CO_2 than in the combustion of pure nitrocellulose. The formation of CO_2 is more desirable, since that process liberates much more heat than the formation of CO. Theoretical considerations and practical tests indicate that the effect of 1 per cent alcohol in

reducing the energy per pound of nitrocellulose is equal to the effect of 2.5 per cent inert material.

Similarly 1 per cent of stabilizer, which is higher in carbon content than alcohol, is considered equal to the effect of 4 per cent of inert matter. Graphite does not readily take part in the reaction and, therefore, the effect of 1 per cent graphite in reducing the energy per pound of nitrocellulose is considered equal to that of 2.5 per cent inert matter.

The energy per pound of pure nitrocellulose, within reasonable limits of nitrogen percentage, is calculated by means of the following empirical formula:

$$\text{Energy} = 231{,}500\ (\text{percentage of N} - 6.45)\ \text{ft-lb.}$$

In computing the energy of nitrocellulose powder the results obtained by the above formula must be corrected for the effect of moisture, inert material, alcohol, graphite, and stabilizer. This is readily done by converting the percentage of each to the equivalent percentage of inert material, and proceeding as indicated for this effect only.

74. Temperature of the Powder.—Firing tables are based on a temperature of the powder of 70° F. at the time of firing. An increase in this temperature increases the potential and the burning rate of the powder, giving a greater muzzle velocity. Conversely, a decrease in the powder temperature reduces the velocity. A tabulation of the effects of variation from standard powder temperature is incorporated in the tables to enable the necessary corrections to be made in the firing data. It is thus desirable to know within some degree of accuracy the temperature of the powder at the time of firing. To reduce inaccuracies from this source the powder should, whenever possible, be left in the magazine or place of storage until shortly before firing. A thermometer should be kept in the place of storage in close proximity to the powder. After removal to the vicinity of the guns the powder should be protected from rapid change of temperature by covering over with canvas.

75. Dimensions of the Charge.—Experience with major caliber weapons using separate loading charges with base igniters has shown that considerable velocity dispersion and, in some instances, excessive pressures may result unless ample space is left between the outside of the charge and the walls of the chamber to provide free passage for the igniting flame. Regulations prohibit the use of any base igniting charge or section thereof which exceeds the maximum allowable diameter as determined by gages furnished by the Ordnance Department.

DETERMINATION OF VELOCITIES AND PRESSURES

The use of interior ballistics formulas and the fundamental relations which have been discussed enables the theoretical calculation of pressures and velocities in the gun and of phenomena associated with gun firings. Ballistic theory is based upon experiment and test; upon data obtained by observation and analysis of firings. Likewise, theoretical calculations must be checked by actual firings.

In the testing of propellants, ammunition, and guns incident to their development or to their acceptance for service use, and in connection with investigative work and research in the field of ballistics, the measurement of velocities and pressures under gun-firing conditions is necessary. Ballistics is a highly specialized science, dealing with velocities, pressures, and conditions not ordinarily encountered in other fields, and requiring special instruments and equipment for their accurate measurement and recording.

Photographic and spectrographic methods of analysis have been used successfully for the study of the phenomena related to the combustion of fuels in internal combustion engines. Inability, thus far, to provide optical windows of sufficient strength to withstand the explosion of propellants has prevented the application of these methods to the study of interior ballistics problems. Such application, should suitable equipment become available, might include observation of the process of ignition and burning of all propellent compositions and types of granulations, study of the origin and action of shock waves, determination of temperatures and the immediate products of explosion at these temperatures, and the investigation of other phenomena under actual gun conditions.

Instruments capable of recording, with reasonable accuracy, the maximum powder pressures and muzzle velocities have been available for a number of years. Modern ballistic work, however, demands instruments of greater accuracy and wider applicability. Their use has assisted in the correction of ballistic hypotheses, the formulation of more rational ballistic theory, and the more accurate checking of theoretical calculations and practical testing of designs of material. The following discussion covers only the instruments in general use.

76. Velocity Measurements.—There is continued linear acceleration of the projectile for a short distance after it leaves the muzzle, due to the velocity and pressure of the powder gases emerging from the bore. Also, the effect of the muzzle blast is felt a considerable distance, especially in the larger weapons. Accordingly, the usual procedure is to determine the velocity of the projectile not at the muzzle but at a point a short distance beyond, where any errors due to the above causes will

be eliminated and no damage to apparatus will result. The velocity obtained is called the *instrumental velocity* at the specified known distance from the muzzle. From this value, by exterior ballistics calculations, the corresponding theoretical muzzle velocity, and the velocities at any point in the trajectory, may be determined.

Velocity, as such, is not measured directly by the instruments, but is determined indirectly by measuring the time interval required for the projectile to travel a short known distance. The velocity, so obtained, is taken as that existing at the midpoint of the distance. The instrument used is called a *chronograph*. It measures accurately the very short time interval required for the projectile travel, by recording the distance traveled during the same time by a part of the chronograph apparatus moving at a known speed. Several types of instruments, employing different means and methods of time and distance measurement, will be discussed.

77. Le Boulengé Chronograph.—This instrument, shown diagrammatically in Fig. 20, measures the elapsed time between the successive ruptures of two independent electric circuits, caused by the passage of the projectile through two screens located at known distances from the muzzle of the gun. The minimum permissible distance of the first screen varies from approximately 50 ft. for cannon of smaller calibers to 300 ft. for the 16-in. gun. The distance between screens varies with the velocity, roughly between 150 ft. and 250 ft. for cannon. The time interval is measured at the chronograph by recording the distance dropped by a freely falling rod in the time required by the projectile to pass from the first to the second screen.

The chronograph proper is usually permanently housed at some distance from the firing point. It consists, essentially, of a brass column mounting two electromagnets A and B connected with the first and second screens, respectively. The magnet A supports the long *chronometer rod* on which is slipped a zinc or copper tube called the *recorder*. Magnet B, which supports the short *registrar rod*, is mounted on a bracket whose vertical position on the column may be adjusted. At the bottom of the column is a flat steel spring which carries a knife at its outer end. The spring is held in the cocked position by a trigger; when released, either by hand or by the falling registrar rod, the knife makes an indent on the recorder.

The instrument being set up, the first step is to locate a zero mark on the recorder. This is done by releasing the trigger, the rods remaining suspended from the magnets. The next step is to measure the time required for the instrument to make a record. Both circuits are broken simultaneously by means of the *disjunctor* switch, and both rods fall.

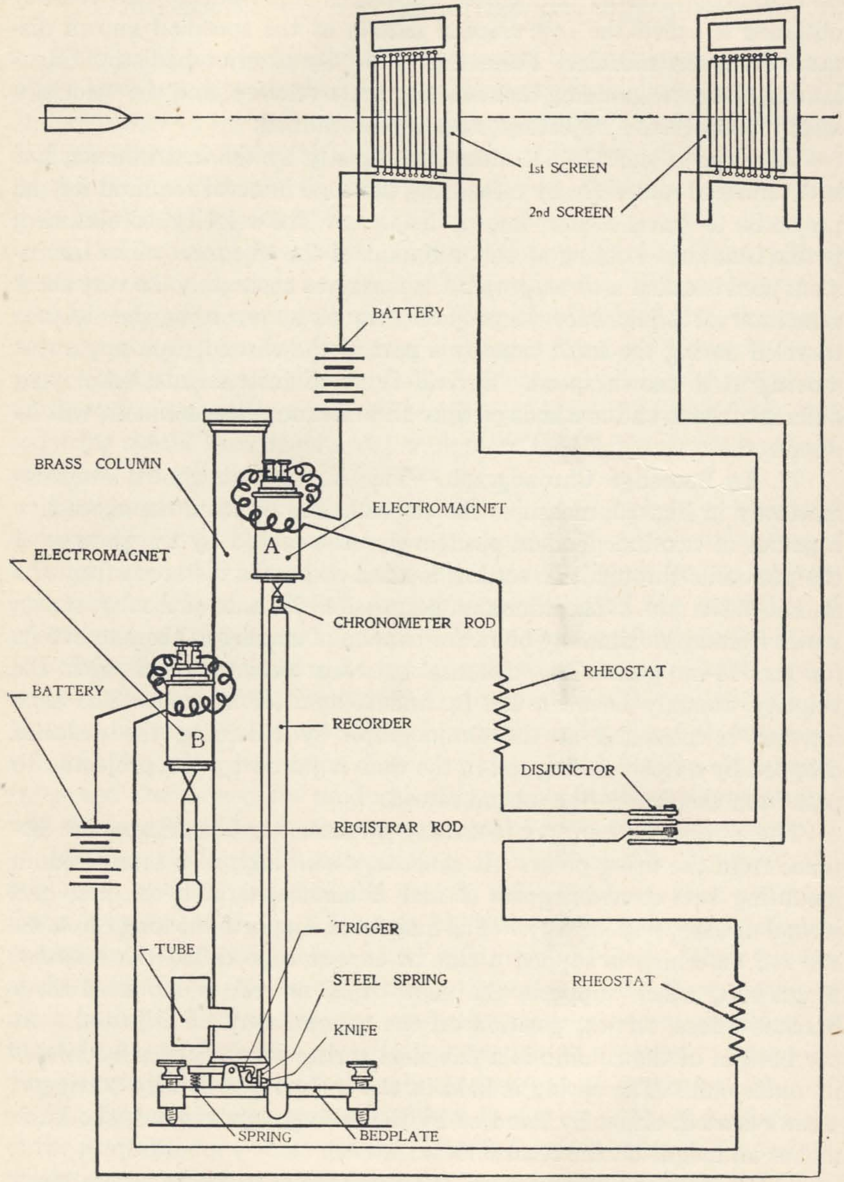

FIG. 20.—Electrical Connections of Le Boulengé Chronograph.

When the registrar strikes the trigger, a *disjunction* mark is made on the falling recorder, at a height h_1 above the zero mark. From the relation $t_1 = \sqrt{\frac{2h_1}{g}}$, the instrumental dead time, which is fixed, is determined.

The instrument is now reset for measuring the projectile velocity. When the projectile passes through the first screen, the circuit of magnet A is broken and the chronometer starts to fall; before it has fallen too far, the circuit of magnet B is broken by the passage of the projectile through the second screen, the registrar falls, the trigger is tripped, and a new mark is made on the falling recorder at a height h_2 above the zero mark. The corresponding time, $t_2 = \sqrt{\frac{2h_2}{g}}$, is the time of flight of the projectile between the screens plus the fixed instrumental dead time.

The time interval between screens is, therefore,

$$t = t_2 - t_1 = \sqrt{\frac{2h_2}{g}} - \sqrt{\frac{2h_1}{g}} \tag{26}$$

and the velocity at the midpoint is

$$v = s/t = \frac{s}{\sqrt{\frac{2h_2}{g}} - \sqrt{\frac{2h_1}{g}}} \tag{27}$$

where s is the actual distance between the screens. The necessary correction factor is then applied to this instrumental velocity to determine the muzzle velocity.

Under favorable conditions the Boulengé chronograph is capable of measuring short time intervals with a mean error of 0.0001 second, corresponding to an error of about $\frac{1}{4}$ of 1 per cent in determining muzzle velocities. In actual practice at the proving ground, three separate circuits are wound on each screen and three chronographs are operated simultaneously, the accuracy of the results being increased by taking the mean of the velocities. Tables and charts have been prepared to simplify the calculations and the reduction of instrumental velocities to muzzle velocities.

Difficulty is experienced in obtaining accurate velocity records of very small projectiles, and other projectiles with long points, which may pass between the wires strung back and forth across the screen. The instrument cannot be used to measure the velocity of projectiles equipped with very sensitive fuzes.

For determining velocities of small arms weapons, the first screen is replaced by a single fine copper wire stretched across the path of the bullet at a point 3 ft. from the muzzle. The second screen is replaced by a circuit breaker, consisting of a steel plate on the back of which is mounted a bracket holding a steel ball in a shallow depression. At rest, the ball bridges two contacts, closing the electric circuit. The impact of the bullet against the plate, however, dislodges the ball and breaks the circuit. The ball then rolls back to its original seat and the circuit is closed for the next shot.

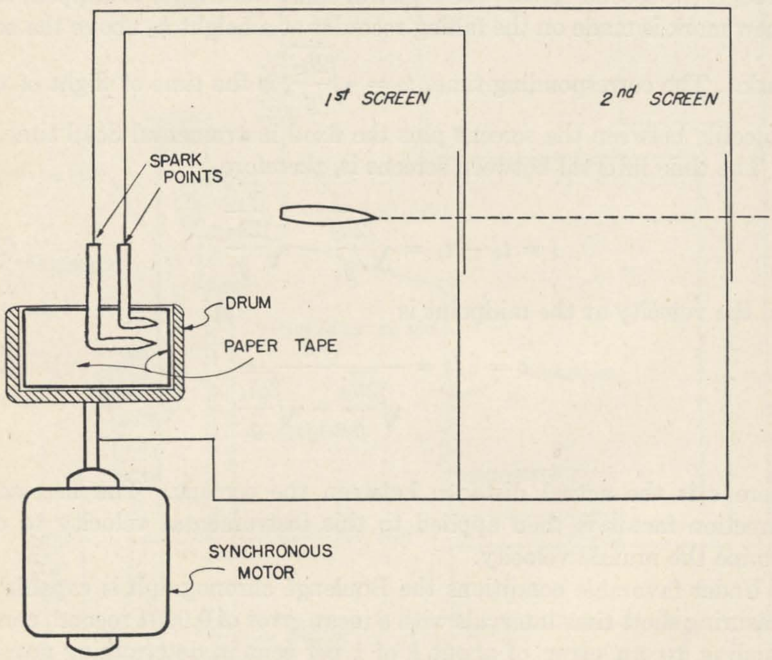

Fig. 21.—Schematic Diagram of Aberdeen Chronograph.

78. The Aberdeen Chronograph.—This instrument, shown diagrammatically in Fig. 21, differs basically from the Boulengé chronograph, in that the projectile closes successively the circuits as it passes through two or more screens, and the time interval is measured on a drum spinning at constant known speed.

Each screen consists of two sheets of tin foil insulated from each other; the circuit is closed when the penetrating projectile is in momentary contact with both sheets. Each circuit includes a power source for the primary circuit, together with coils and condensers to induce a

high potential in the secondary circuit and to intensify the spark from the spark point to the rotating drum.

The drum is mounted on the shaft of a synchronous motor, running at a constant speed of 1800 r. p. m. A frequency meter is provided to permit correction for any variation from the standard power frequency at the instant of firing. A *record strip* of paraffin-coated paper, equal

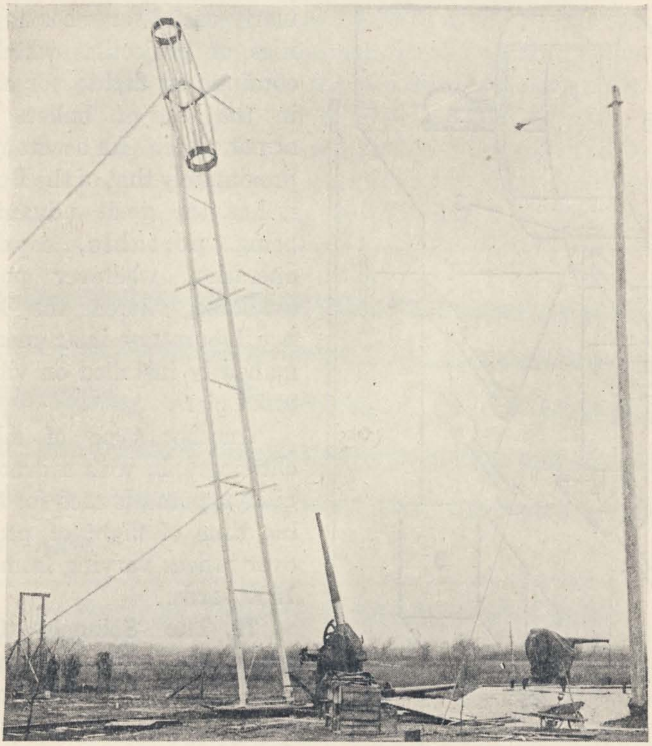

FIG. 22.—Firing Antiaircraft Gun for Velocity, Using Solenoids on Boom and Solenoid Chronograph.

in length to the inner circumference of the drum, is held against the drum during rotation by centrifugal force.

Each circuit is closed, in turn, as the projectile passes successively through the screens, and a spark jumps from the proper spark point to the drum, puncturing the record strip and leaving a mark. By measuring the distance between two spark perforations, and knowing the linear speed of the record strip, the time of flight between the corresponding two screens may be determined; from this, knowing the distance between the screens, the velocity at the midpoint is determined.

By means of a special ruler, distance between two perforations on the strip may be read directly as a velocity value. This must be corrected for any small variation in standard drum speed. The corresponding muzzle velocity is then computed or obtained from available tables.

The Aberdeen chronograph is used ordinarily for measuring velocities of small arms, but has been used successfully with larger calibers, including 37 mm. It is particularly useful for recording velocities of projectiles which must continue in flight; for example, in the test of bullets against armor plate. Its accuracy is approximately that of the Boulengé; it has the great advantage of being portable, capable of operation wherever power is available, whereas the Boulengé is a laboratory instrument, permanently installed on vibration-proof piers.

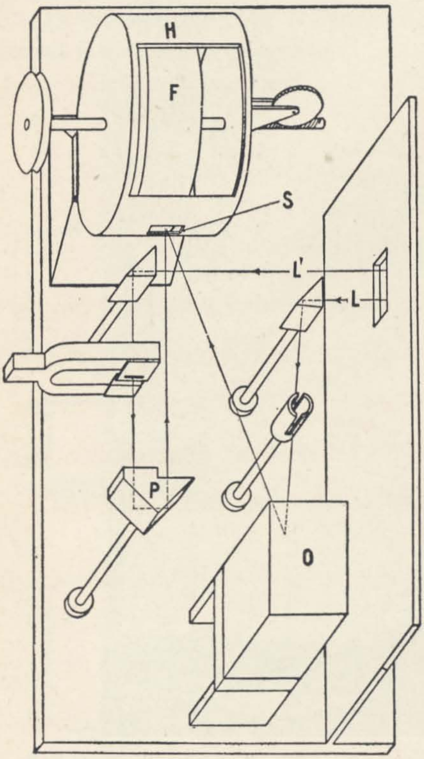

Fig. 23.—Oscillograph Camera.

Another type of Aberdeen chronograph, with a drum speed of 15 r. p. m., is used for measuring time of flight of projectiles over ranges varying from 300 to 1500 yards.

79. The Solenoid Chronograph.—If a magnetized projectile is fired through separate coils of wire, an electromotive force is generated in each coil. If some manifestation of the resulting instantaneous currents can be recorded, as on a photographic film moving at a given rate, time-distance relations will be established and a time record of the passage of the projectile through the coils provided.

These principles are embodied in the Solenoid chronograph, the coils or solenoids being mounted a known distance apart in the framework, as shown in Fig. 22, and at a known distance from the gun. Each coil is connected to the galvanometer of an *oscillograph*, Fig. 23, which records the events. The oscillograph consists essentially of a delicate mirror galvanometer, a tuning fork vibrating at a known high frequency,

and a photographic apparatus for recording time and galvanometer deflection.

Rays of light L from an arc lamp are deflected by the first prism and pass through a slit, to exclude the outer rays, to the mirror of the galvanometer at O. They are reflected at O and pass through the shutter S to the photographic film F covering the drum. Rays L' from the same light source also pass to a second prism where they are deflected through slits in two plates attached to the prongs of the tuning fork, to the prism P, and thence through the shutter to the film. Twice in each cycle of the tuning fork, the two slits are in coincidence, permitting passage of the light. If a 500-cycle fork is used, the time interval between the lines photographed on the film will be 0.001 second. The drum not only rotates, but is translated axially at the same time.

A typical oscillograph record is shown in Fig. 24. The timing lines

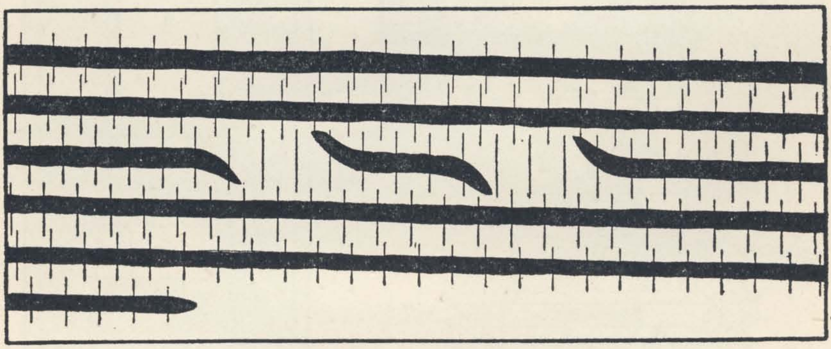

FIG. 24.—Record Film Made by the Solenoid Chronograph.

are recorded as long as the apparatus is in operation. When there is no current to deflect the galvanometer mirror, the film shows a broad straight band. The current generated in each solenoid coil by the passage of the projectile, however, deflects the galvanometer and causes a break in the band. The time consumed in the projectile passage is determined by counting the number of timing lines between the midpoints of the two breaks. The distance between the coils being known, the mean velocity of the projectile between the coils may be determined, and from this the muzzle velocity obtained.

The Solenoid chronograph has shown consistently more uniform results and greater precision than any other type. It is capable of measuring velocities with an accuracy of about 99.98 per cent. Its use is warranted where a high degree of accuracy is required. It has other advantages also; the re-wiring or replacing of screens is not necessary after each round, velocity records can be made with projectiles fitted

with supersensitive fuzes, and the making of velocity records at high gun elevations is simplified. These advantages have led to increased general use. The record is not immediately available, however, as it is when the Boulengé or Aberdeen chronograph is used.

80. Pressure Measurements.—As pointed out in Section 58, the maximum permissible interior pressures are specified for each gun. It becomes necessary, therefore, to provide methods of determining these pressures for every propellant-projectile-gun combination. The maximum powder pressure is built up so quickly, and is maintained for such a brief interval of time, in some cases for approximately 0.0001 second

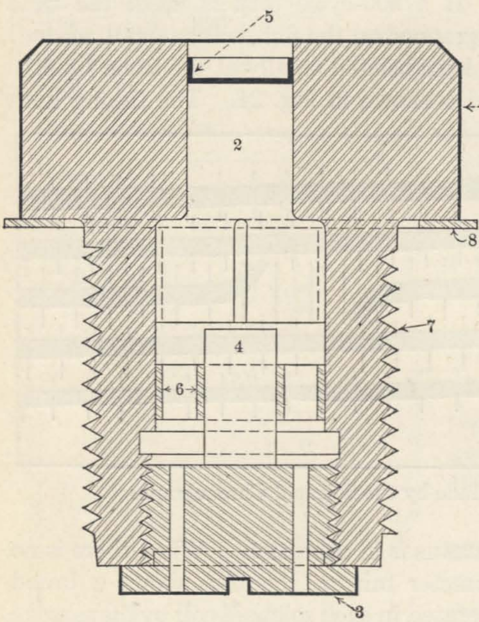

FIG. 25.—Fixed Crusher Gage.

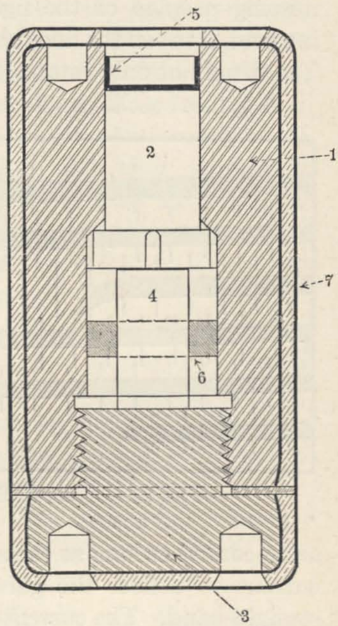

FIG. 26.—Loose Crusher Gage.

only, that precise measurement of its exact magnitude is not practicable with instruments now available. Several methods are employed, however, which, although they may not record the true pressure levels, nevertheless record *comparative* pressures consistently. Instrumental calibration is based upon the effects produced by the slow application or sudden release of known loads; it is apparent, therefore, that, when used to measure pressures in the gun, which are developed and dissipated in such a brief time interval, the results obtained are comparative only.

81. The Crusher Gage.—The two types of gages used are illustrated in Figs. 25 and 26. The gage consists of a body or housing (1), in which

is fitted closely a steel piston (2), which transmits the powder gas pressure to a small copper cylinder (4) held in a central position by a spring or rubber ring (6), and supported by an anvil which is part of the closing plug (3). A copper obturating cup (5) prevents gas leakage past the piston to the interior of the gage. The maximum powder gas pressure is measured by the amount of permanent compression produced in the copper cylinder. The larger gage is used in major caliber cannon, being screwed into a threaded recess in the inner face of the breechblock. The smaller gage is used in smaller cannon, being placed loose in the powder chamber at the rear of the charge. It is covered with a soft copper shell (7) to prevent damage to the bore of the gun in firing.

Figure 27 illustrates the application of the crusher gage to the measurement of pressures in small arms. A special barrel is used, with

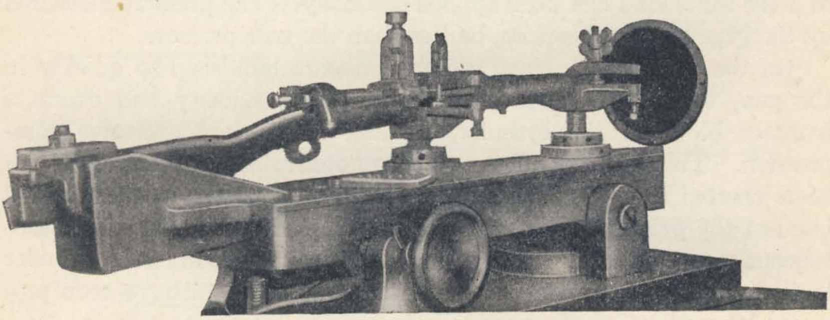

FIG. 27.—Small Arms Rest and Pressure Gage.

standard chamber and bore dimensions. A hole bored radially through the wall of the chamber permits the powder gas to operate against the piston of the crusher gage rigidly mounted on the outside of the barrel. As in the cannon gages illustrated, pressure is recorded by compression of the copper cylinder.

Calibration of Copper Cylinders.—The copper cylinders used are cut in half-inch lengths from rods made as uniform as possible in dimensions and physical properties. A large number of cylinders from each lot are tested in a static testing machine, and tables are prepared showing the average permanent set or amount of compression produced by each static load. It is assumed that the cylinder compression obtained in firing is due to a pressure on the gage piston equal to the static load that produces the same compression in the testing machine. Therefore, the maximum pressure per square inch in the gun, indicated by any compression, may be obtained by dividing the corresponding static load by the area of the gage piston. In this manner, tables termed *tarage*

tables are prepared and made available for general use by the service, showing the powder pressures per square inch corresponding to the compressions. A micrometer caliper is used to measure the lengths of the copper cylinder before and after firing; entering the table with this measured difference in length, the maximum powder gas pressure in pounds per square inch is found.

Accuracy of Pressures.—Calibration of cylinders is based upon a slowly applied load, the final load for each tabulated compression being retained for several seconds. In the gun, the pressure is quickly applied and only momentarily existent. An appreciable length of time is required for the copper to flow and to become set at its full compression corresponding to any load; since the pressure is not sustained so long as this in the gun, the cylinder will not be permanently compressed as much as if the same load had been applied statically. The pressure measured by the gage would, therefore, be less than the true pressure.

On the other hand, since the gas pressure builds up so quickly in the gun, the piston moves with considerable velocity and exerts a hammer blow on the cylinder, tending to produce excessive compression. This hammer effect has been noted when crusher gages have been inserted in tapped holes along the bore of a gun; as the rotating band of the projectile passes each hole, the full gas pressure is instantaneously exerted on the gage piston. The compression of the cylinder is distinctly greater under such conditions than would have been produced by application of a gradually increasing pressure.

The pressures registered by crusher gages placed in the chamber of a gun are accepted as being only about 80 to 85 per cent of the true maximum pressure. However, as a *comparative* measure, the gage is satisfactory, and affords a simple and convenient means of determining relative values of gun pressures.

82. The Piezo-electric Gage.—The crusher gage measures only the maximum pressure to which it is subjected. The piezo-electric gage is used when it is necessary to establish an accurate and continuous record of the time-pressure relation in the gun. The action of the instrument is based upon a characteristic property of certain crystals, that when the crystals are compressed along certain principal axes, an electrostatic charge is developed which is directly proportional to the pressure applied.

The gage, Fig. 28, consists essentially of a series of quartz discs, the plane faces being cut exactly parallel to each other and perpendicular to the electric axis of the crystal. The discs are separated by thin metal plates, and are assembled so that, alternately, positive and negative faces are in juxtaposition. The positive plates are connected to one

terminal of the gage and the negative plates are connected and grounded to the gage housing. The assembled discs are placed in a transparent bakelite cylinder sealed with wax at both ends to prevent entrance of moisture or oil. The ball joint formed by the hemispherical metal piece and its seat prevents any cross or unequal strain in the column of discs. For use, the gage is screwed into the forward face of the breechblock. The pressure of the powder gas transmitted by the piston to the pile of discs develops an electric charge proportional to the pressure. Leads are run from the positive and negative terminals to the recording apparatus.

Several types of recording apparatus have been developed. The same oscillograph and drum camera described with the Solenoid chrono-

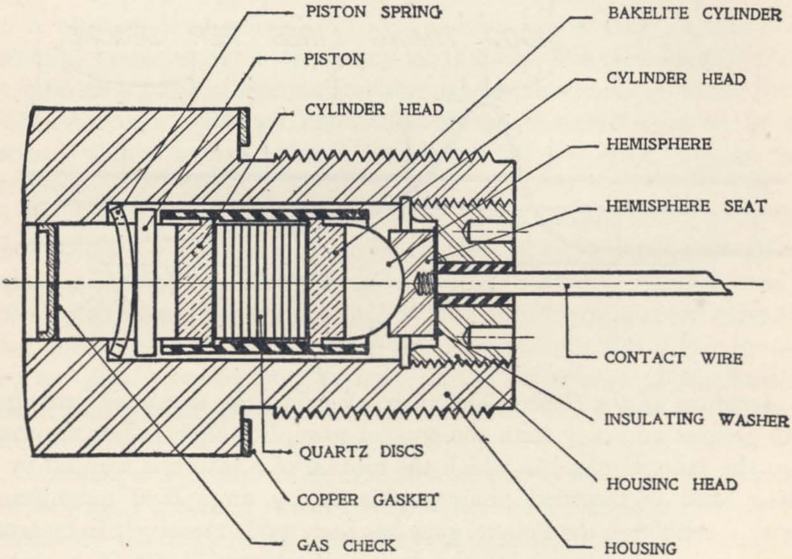

FIG. 28.—Piezo-electric Pressure Gage.

graph may be used, the degree of deflection of the beam of light from the mirror galvanometer, as recorded on the film, being directly proportional to the pressure on the gage. Or the cathode-ray oscillograph may be used. In this case, the positive and negative leads from the gage are connected to the same condenser, which is connected in turn to a vacuum tube amplifier and a cathode-ray oscillograph tube. The change in the output voltage of the amplifier is proportional to the charge on the condenser coming from the gage. This output voltage is impressed upon the deflecting plates of the cathode-ray oscillograph, causing a deflection of the electron beam proportional to the pressure on the gage. This deflection is recorded on a photographic film.

Figure 29 is a cathode ray oscillogram showing the pressure-time curve for the U. S. Rifle, Cal. .30, M1903.

The gage is calibrated in a hydraulic testing machine, so arranged that the pressure can be released suddenly. This produces an electrostatic charge equal in magnitude but opposite in sense to that produced by the application of an equal pressure. The relation between charge and pressure is thus determined and a gage calibration curve may be constructed. From this, and the known relation between charge on the condenser and cathode-ray deflection, the gun pressure may be calculated from the recorded oscillogram.

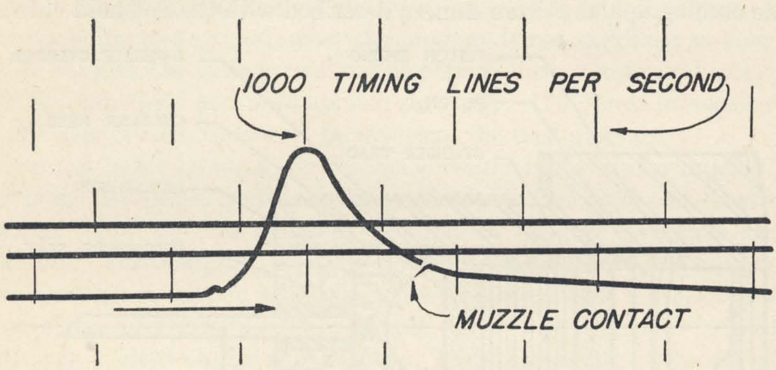

FIG. 29.

Accuracy of the Gage.—The piezo-electric gage measures pressures with greater accuracy than the crusher gage, but slightly less accurate than the Petavel gage, in which the motion of a piston is resisted by a spring, and is recorded photographically by an optical magnifying device. Although the Petavel gage has been used extensively in measuring pressures developed by the explosion of propellants in a closed chamber, it has little application to measurement of actual gun pressures because the motion in recoil affects the results.

The piezo-electric property of crystals was first used to measure explosion pressures in 1917, by Sir J. J. Thomson of England. The development of the gage for use at the Aberdeen Proving Ground was begun in 1919 by G. F. Hull, and has been continued by E. C. Eckhardt, J. C. Karcher, R. H. Kent, and A. H. Hodge. Joachim and Illgren of Germany have made important contributions to the development. The gage is still a laboratory instrument, not suitable for routine general use.

CHAPTER IV

METALS

PHYSICAL QUALITIES OF METALS

A clear understanding of the properties which they possess is an essential prerequisite to the study of metals. Physical qualities will be used as a basis of comparison throughout this chapter of the book. Furthermore, a thorough knowledge of the characteristics to be described will be necessary as a foundation for the study of gun construction.

83. Qualities of Metals.—*Elasticity* is the property or power of a body to recover its original form on removal of an applied load. If the recovery is complete, the body is said to be "perfectly elastic"; that is, the *elastic strain* set up by the applied load entirely disappears when this load is removed. If the load per unit area exceeds the elastic limit of the material, recovery will be only partial on release of the load, in which case the strains set up by the load will be of two kinds, *elastic* and *permanent.*

Plasticity.—Permanent deformation of any body involves displacements within the body, during which the mutual actions between the atoms are overcome. The property of plasticity depends upon the ability of such displaced atoms to re-establish mutual actions of attraction and repulsion. This ability is a conspicuous characteristic of a liquid. A material which can undergo an indefinitely large number of permanent deformations is said to be "perfectly plastic."

The materials considered in this chapter, when subjected to increasing stress, at first behave elastically, but, after the stress reaches the elastic limit, the material begins to alter its shape or form. Such materials are said to be "imperfectly plastic," but the permanent deformations are considered as plastic actions. For materials which have a well-defined yield point, such as ductile steel, the change from a state of nearly perfect elasticity to one of considerable plasticity takes place suddenly. For nearly all engineering uses, it is desirable that materials used should remain elastic under working conditions.

Ductility.—The property of being permanently extended, without rupture, by a tensile stress, as in wire drawing. There is no standard of ductility, but this property is expressed in relative terms of "elongation," "reduction of area," and the angle through which a specimen can be bent or twisted without rupture.

Malleability.—The property of being permanently extended in all directions without rupture, as when the metal is hammered or rolled.

Brittleness.—The property of being readily broken or ruptured under a suddenly applied load.

Toughness.—The property of resisting rupture under a suddenly applied load; of possessing flexibility without brittleness. It is the name given to the combined properties of strength and plasticity in a material.

Hardness.—The property of being able to resist permanent deformation. It is resistance to plastic deformation and is measured by resistance to indentation and penetration, resistance to scratching and abrasion, and in many other ways. A definite relation exists between hardness and tensile strength.

84. Modulus of Elasticity.—The *modulus of elasticity* is the ratio, within the proportional limit of a material, of stress to the strain produced by that stress. This ratio is often referred to as Young's modulus of elasticity or as the stretch modulus. It is usually denoted by E and measured in pounds per square inch. It is a measure of the *rigidity* of a material.

There are three moduli of elasticity for any material: the modulus in tension, the modulus in compression, and the modulus in shear. For ductile metals, the value of the modulus of elasticity in tension is nearly the same as the modulus of elasticity in compression. The value of the modulus of elasticity in shear is smaller than the value of the modulus of elasticity in tension or compression.

Young's modulus in tension is referred to when the term "modulus of elasticity" is used without any qualifying word. For steel, Young's modulus is about 30,000,000 lb. per sq. in.

85. Stress and Strain.—*Stress* is defined as an internal force acting between adjacent parts or sections of a body being considered. It may be produced by a force or forces external to the body or may be due to the condition of the body itself, such as would be caused by mechanical or thermal treatment. There are three kinds of stress: tensile, compressive, and shearing. A shearing stress so deforms the body that an elementary square in a plane perpendicular to the shearing surface and parallel to the action line of the shearing stress has one diagonal lengthened and the other shortened. Flexure or pure bending involves both

tensile and compressive stresses. Torsion involves shearing stress. Many complex combinations of these three elementary stresses are found in mechanics.

Stresses are sometimes designated as *unit stresses* to indicate unit force rather than total force acting on an area. They are measured in *pounds per square inch* of surface normal to the action line in tension and compression, and parallel to the action line in shear.

Strain is the deformation or change in dimension or shape produced by the action of stress. Each kind of stress produces a corresponding strain. A tensile stress causes elongation; a compressive stress causes shortening. Shear strain consists of a tangential sliding of the parts under shear stress. Similar to unit stresses, *unit strains* must be distinguished from total strains. They are measured by the amount of deformation per unit of length, such as inches per inch. Thus a tensile stress of 60,000 lb. per sq. in. may produce a strain of 0.002 in. per in.

A Stress-strain Diagram is a curve plotted with values of unit stress as ordinates and corresponding values of unit strain as abscissae. It is sometimes more convenient to plot the actual loadings against total deformations, giving a *load-deformation* diagram.

Limits.—During the application of load to a piece of steel, it is found that the stress-strain diagram is at first a straight line, and the unit strain is directly proportional to the unit stress. The termination of the straight line of the diagram indicates the proportional limit of the metal; and *proportional limit* is defined as the greatest unit stress which a metal is capable of withstanding without deviating from the law of proportionality of stress to strain.

The *elastic limit* is the greatest unit stress which a material is capable of withstanding without a permanent deformation remaining upon complete release of the load.

The *yield point* is the unit stress in a material at which there occurs a marked increase in strain without a proportionate increase in stress. Only ductile materials exhibit a marked yield point. For this point the stress-strain diagram shows a line that is usually horizontal. For some materials it even dips below this horizontal.

Figure 30 shows that the elastic limit, the proportional limit, and the yield point have approximately the same value. Determination of the elastic limit is a tedious operation since it requires the application and release of small increments of load to observe the start of permanent deformation. The proportional limit, readily determined from the stress-strain diagram, is customarily accepted in lieu of the elastic limit. Frequently the yield point, which is very easily observed by the drop of

the beam of the testing machine or the rapid increase of strain on the extensometer, is accepted as a substitute for both in structural steels.

The *tensile strength* is the maximum unit stress which a material is capable of withstanding. It is computed from the maximum load and the original cross-sectional area measured in square inches. If the metal is left under this stress, rupture occurs. This stress is sometimes referred to as the *ultimate strength* of the material.

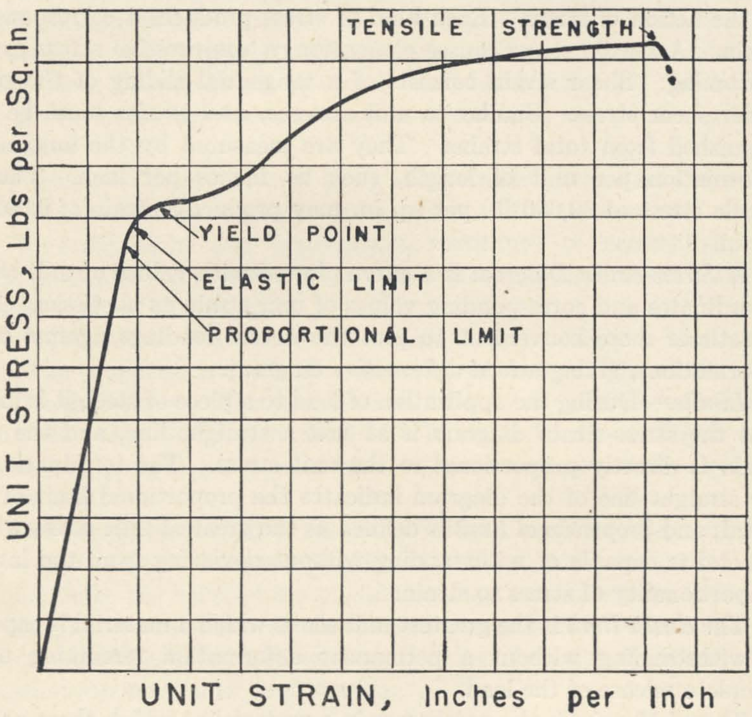

FIG. 30.—Stress-strain Diagram.

The *compressive strength* is the maximum compressive unit stress which a material is capable of withstanding.

The *percentage elongation* is the difference in the gage length of a specimen before being subjected to any stress and after rupture, expressed as a percentage of the original gage length.

The *percentage reduction of area* is the difference between the original cross-sectional area and the least cross-sectional area after rupture, expressed as a percentage of the original cross-sectional area.

USEFUL METALS AND ALLOYS

The most useful metals are iron, copper, and aluminum. Smaller amounts of nickel, cobalt, molybdenum, chromium, zinc, lead, tungsten, antimony, manganese, and tin are also very essential. However, only small quantities of any of the above metals are used in their commercially pure forms. The great majority of useful metallic materials are formed from combinations of the above metals, known as *alloys*.

86. *Alloys* are usually made by mixing two or more metals in their liquid state. If the metals chosen have the power of dissolving in each other when liquid, the solution, when allowed to solidify, will form an alloy. Metals that do not dissolve in each other when liquid will not form an alloy when they solidify.

An alloy has the appearance of a homogeneous solid. Microscopic examination, however, may show the presence of several types of crystals, or grains, depending upon the nature of the process of solidification. Such grains differ from one another in shape, size, and strength; and also in the strength of their adherence to one another. Hence, the properties of an alloy, such as strength, ductility, and resistance to impact, are determined by the properties of an aggregate rather than by the properties of a number of homogeneous grains.

Typical examples of useful commercial alloys are:

(*a*) Brass—an alloy of copper and zinc.
(*b*) Duralumin—an alloy of aluminum and copper.
(*c*) Steel—an alloy of iron and iron carbide.

THE OCCURRENCE AND MANUFACTURE OF METALS

87. Occurrence.—All but a few of the metals are found in combined form in the earth's crust. When the deposits are near the surface the *oxide* of the metal predominates. At greater depths the *sulphide* is more common. In both cases the compound of the metal is usually found mixed with a large amount of undesirable dirt and rock.

Four operations are required to obtain the metal in useful form. (1) The ore is obtained by *mining*. (2) The percentage of valuable mineral is raised and the excess rock is discarded by *concentration*. (3) The oxide is *reduced*. (4) The metal is *purified*. In the sulphide ores a fifth step is necessary to convert the sulphide to an oxide before reduction. The first two operations are of interest primarily to the mining engineer.

The methods used for reduction and purification may be grouped in three classes, but the details of operation in any class vary widely

depending upon the particular metal to be treated. Reduction and purification are accomplished (1) by *fire*, in which the oxide is melted and reduced by the presence of carbon, or the metal is purified by re-melting and treating to oxidize or to deoxidize it; (2) by *chemical* methods, in which the oxide or metal is taken into solution, treated, and then precipitated in a more desirable condition; and (3) by *electrolysis*, in which the metal is reduced from its oxide, or is separated from impurities and deposited at the electrode. A brief outline of the methods used to obtain a few of the more important metals will serve to illustrate applications of the above groups.

88. *Aluminum* is reduced from its oxide and deposited in a relatively pure state by electrolysis. All clay banks are potential ores of aluminum, but the anhydrous oxide required for electrolytic reduction must be so pure that a general use of clay is not attempted. Bauxite, an impure hydrate of aluminum oxide, is used as the ore. Purification of bauxite is accomplished by chemical methods and is the most difficult step in the manufacture of the metal.

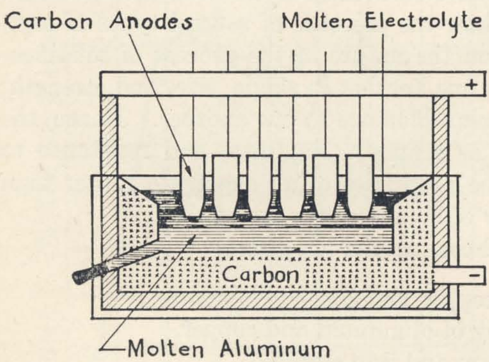

FIG. 31.—Electrolytic Refining of Aluminum.

After purification, the oxide is added to a bath of molten sodium aluminum fluoride, cryolite, in a carbon-lined electrolytic tank such as that shown in Fig. 31. Molten aluminum is deposited at the bottom of the tank, the cathode, and is drawn off as desired. The product, which is approximately 99 per cent Al, is used as it is or is re-melted with other metals to form one of the numerous and important aluminum alloys. Sodium and other metals too high in the electromotive series for electrolysis in the presence of water are also obtained by electrolysis in fused salts.

89. *Copper* is present in numerous minerals from the deposits of which it is economic to recover the metal. Details of the manufacture depend on the type of ore to be treated. In general, the sulphide ores are found in combination with sulphides of iron. The ores are roasted at about 650° C., to cause oxygen from the air to unite with sulphur and form SO_2 and SO_3. The sulphur content is thus reduced to a point where the ore may be smelted and the iron sulphide and copper sulphide separated from the remaining impurities. The copper-iron sulphide—

called *matte*—contains the gold, silver, and other precious metals that were present in the ore. The matte is placed in a pear-shaped vessel called a *converter* and air is blown through the liquid to oxidize the iron and to combine with all the rest of the sulphur. The resulting metal is known as *blister copper* because of the appearance caused by bubbles of excess air entrapped when the metal solidified. It contains 98 per cent Cu.

Because of the advantages of purity in copper used for electrical work, blister copper is refined by re-meltings or by a series of electrolyses. A modern electrolytic plant is shown in Fig. 32. The blister

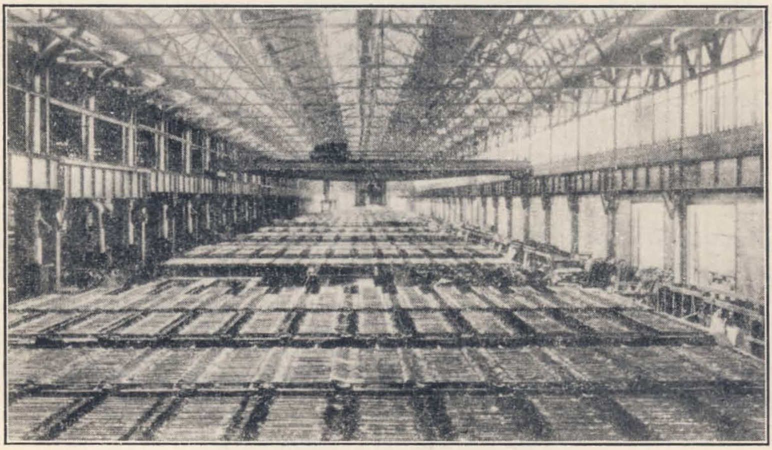

FIG. 32.—Electrolytic Refining of Copper.

copper is cast into anodes and the refined copper is deposited at the cathode. The electrolyte is dilute H_2SO_4 and the potential is maintained at such a level that copper will deposit on the cathode, lead and other impurities above copper in the electromotive series will remain in solution, and gold and silver will drop down and can be recovered from the sludge in the bottom of the tank. Copper subjected to two or three such electrolyses is obtained 99.97 per cent pure and is used for electrical applications. Metal of less purity (99.93 per cent Cu) is obtained after one cycle of electrolysis and is used in the manufacture of brass, bronze, and other alloys containing copper.

90. *Zinc* is obtained by reduction of the oxide in the presence of carbon at temperatures above the boiling point of the metal, or by electrolysis. The zinc vapor is condensed at the mouth of the retort and the liquid is drawn off and cast into slabs for use in the manufacture

of die castings, brass, and for other purposes. A zinc retort is shown in Fig. 33.

91. *Iron* is found as the oxide, hematite (Fe_2O_3), or magnetite (Fe_3O_4). Other ores are of minor importance in this country. The oxide is reduced in a tall shaft furnace known as a *blast furnace* (Fig. 34). Alternate layers of coke, ore, and limestone are placed in the furnace until the shaft is almost full. Preheated air is blown through jets called tuyeres near the bottom of the shaft and the coke is burned to provide heat to melt the charge and C and CO to reduce the iron oxide. The limestone is added in sufficient quantity to combine with the undesirable siliceous materials present in the ore. This combination of basic and acid materials forms a readily fusible *slag*. Reduction of the ore takes place as the charge sinks down through the shaft, and liquid iron and slag drip down and are collected in the hearth of the furnace.

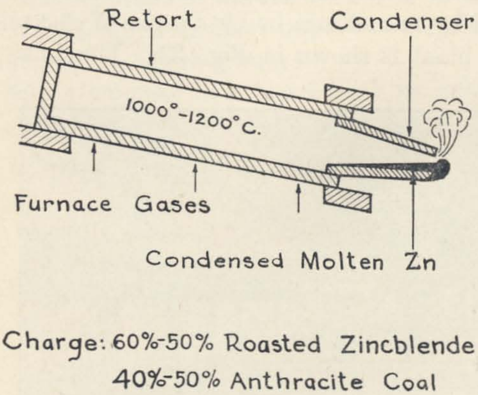

FIG. 33.—Zinc-refining Retort.

Because of its lower specific gravity the slag collects in a layer on top of the liquid iron. The slag and iron are tapped from their respective levels as desired. The iron is run into small blocks known as "pigs" from which it gets the name *pig iron*. The slag is used in the manufacture of cement and for road construction. A modern blast furnace 100 ft. tall produces about 1200 tons of pig iron per day. The raw materials required to obtain this production are: (*a*) 2200 tons of ore, (*b*) 1000 tons of limestone, (*c*) 1000 tons of coke, and (*d*) 75,000 cu. ft. of air heated to about 650° C., (1200° F.). The pig iron produced by the blast furnace contains about 94 per cent Fe. The impurities are chiefly carbon and silicon (3 to 4 per cent C and 1 to 2.5 per cent Si). Small amounts of manganese, sulphur, and phosphorus are also present.

Because of these impurities pig iron is never used as such. It is frequently re-melted in a shaft furnace called a cupola, where it is oxidized to reduce slightly the carbon and silicon contents, and is then cast into useful shapes in the form of *cast iron*. Cast iron is relatively hard and very brittle. It is useful for heavy parts for machines when it is not to be subjected to severe shock or vibratory stresses. By far the

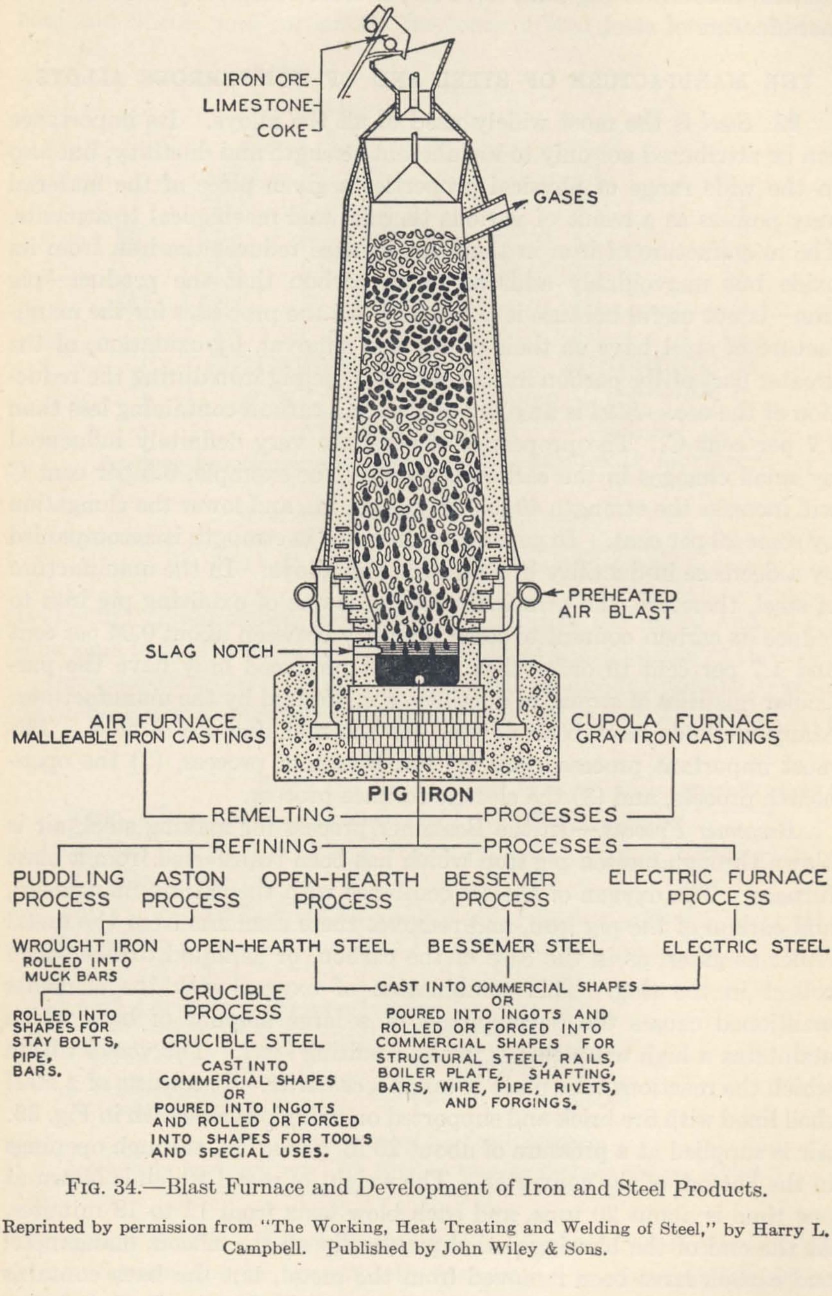

FIG. 34.—Blast Furnace and Development of Iron and Steel Products.

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greatest amount of pig iron, however, is more completely refined in the manufacture of steel.

THE MANUFACTURE OF STEEL AND OF NON-FERROUS ALLOYS

92. *Steel* is the most widely used of all the alloys. Its importance can be attributed not only to its inherent strength and ductility, but also to the wide range of physical properties a given piece of the material may possess as a result of various thermal and mechanical treatments. The manufacture of iron in the blast furnace reduces the iron from its oxide but unavoidably adds so much carbon that the product—pig iron—is not useful because it is brittle. All the processes for the manufacture of steel have as their object the removal, by oxidation, of the greater part of the carbon introduced into the pig iron during the reduction of the ore. *Steel* is an alloy of iron and carbon containing less than 1.7 per cent C. The properties of steel are very definitely influenced by small changes in the carbon content. For example, 0.5 per cent C will increase the strength 40,000 lb. per sq. in., and lower the elongation by some 20 per cent. In general, an increase in strength is accompanied by a decrease in ductility in all metals and alloys. In the manufacture of steel, therefore, the principal problem is one of oxidizing pig iron to reduce its carbon content to some quantity between about 0.04 per cent and 1.7 per cent in order that the steel produced may have the particular qualities of strength, ductility, etc., desired by the manufacturer. Many methods have been devised for the manufacture of steel. The most important processes are (1) the Bessemer process, (2) the open-hearth process, and (3) the electric-furnace process.

Bessemer Process.—In the Bessemer process for making steel, air is blown through molten pig iron which has been transferred from a blast furnace. The oxygen of the air combines with the silicon, manganese, and carbon of the pig iron, and removes these elements from the metal either as gases, as in the case of the carbon, or as liquid oxides which collect in the slag. This combination of oxygen with the elements mentioned causes the development of a large amount of heat which maintains a high temperature in the resulting steel. The vessel within which the reactions take place is called a *converter*. It consists of a steel shell lined with fire brick and supported on trunnions as shown in Fig. 35. Air is supplied at a pressure of about 20 lb. per sq. in. through openings in the bottom of the converter. The weight of metal which is blown at one time is about 20 tons, and each blow lasts from 12 to 18 minutes. At the end of the blowing period practically all the silicon, manganese, and carbon have been removed from the metal, but the bath contains considerable iron oxide as gas in solution. While the metal is being

poured from the converter, additions of ferro-alloys containing manganese and silicon, and carbon (in the form of coal), are introduced into

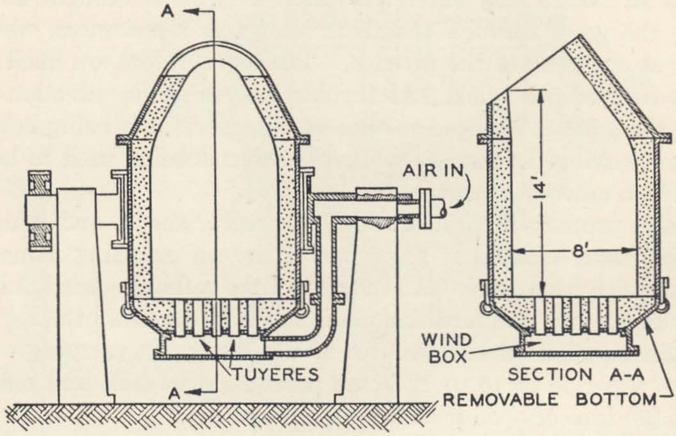

FIG. 35.—Bessemer Steel Converter.

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the metal. These substances serve to deoxidize the metal and at the same time to supply the desired proportions of the elements in the steel.

Open-hearth Process.—In the open-hearth process for producing steel, the metal charges consisting of pig iron and steel scrap are melted on a

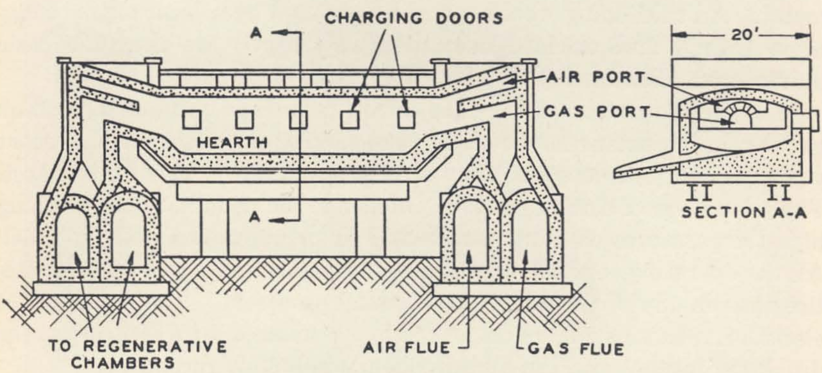

FIG. 36.—Open-hearth Steel Furnace.

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long shallow hearth. In many instances molten iron is transferred from a blast furnace to the open-hearth furnace. The construction of an open-hearth furnace is shown in Fig. 36. The furnace hearth is sur-

rounded by a roof and walls of silica brick. In order to obtain the high temperatures required to melt steel, it is necessary to preheat the fuel and the air before they enter the furnace. This is brought about by passing the gases through chambers known as *regenerators*, which are located at each end of the furnace. The regenerators are filled with a checkerwork of fire brick. At regular intervals, the direction of the flow of the gases is changed so that one regenerator is being heated by the gases leaving the furnace while the other is being used to heat the gases which enter the furnace.

In this process, the elimination of carbon, silicon, and manganese from the metal charges is accomplished by an oxidizing flame or by reactions with iron oxide. At the end of the refining period, additions of ferromanganese and ferrosilicon are made to deoxidize the metal and to obtain the desired composition of the steel. In carrying out this practice, a period of 10 to 12 hours is required to melt and refine one heat of 100 tons of open-hearth steel.

Steel made by the open-hearth process is designated as *acid open-hearth steel*, or as *basic open-hearth steel.* These terms relate to the refractory materials used in the furnace linings and to the composition of the slags produced. Phosphorous and some sulphur are removed from the metal by adding limestone to the furnace charges. This material produces a basic slag in which the phosphorus and, to a lesser extent, the sulphur collect. It is necessary to provide a basic lining for the hearth of the furnace when a basic slag is used for purifying the metal. An acid lining would soon be destroyed by a basic slag. Magnesia (MgO) and calcined dolomite ($CaO.MgO$) are used for basic linings, and silica sand (SiO_2) for acid linings of furnaces.

Electric-furnace Process.—The electric-furnace process has been gaining in importance over other steel-making processes within recent years. A large tonnage of alloy steel is produced in electric furnaces. The advantage of electric-furnace practice is the possibility of obtaining high temperatures without introducing air or impurities from the fuel. All the operating conditions can be more readily controlled in this practice than in any of the other steel-making processes. The two types of electric furnaces which are employed in the manufacture of steel are the direct-arc furnace and the high-frequency induction furnace.

Direct-arc Furnace.—This furnace is constructed of a heavy steel shell which is lined with refractories as shown in Fig. 37. The roof is built separately and can be replaced when necessary. Three electrodes are supported in a vertical position above the furnace and extend through the roof. Connections are made from a three-phase alternating-current supply to the electrodes. The current passes from one

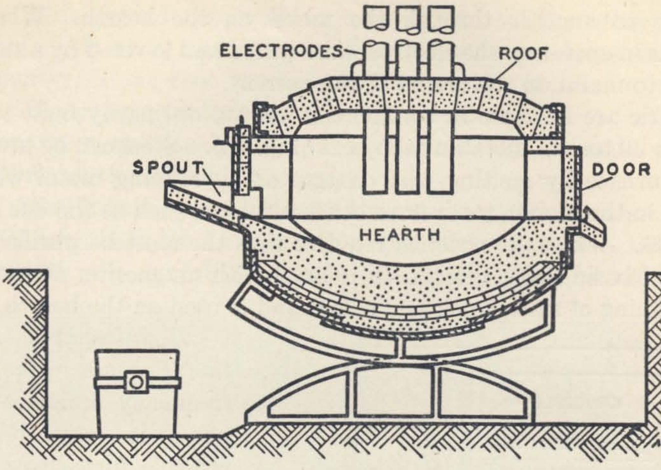

Fig. 37.—Electric-arc Furnace.

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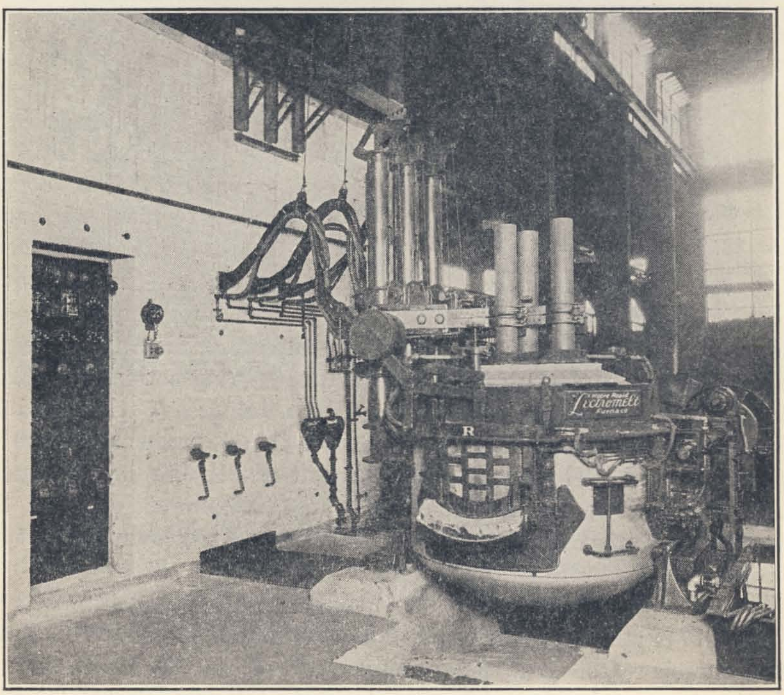

Fig. 38.—Electric Steel-melting Furnace.

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electrode to another through the metal on the hearth. When the furnace is in operation the electrodes are raised and lowered by automatic controls to maintain the arcing of the current.

Electric arc furnaces in commercial use are ordinarily built to melt from 5 to 30 tons of metal in each heat (Fig. 38). Steel can be produced in this furnace by melting cold charges or by refining metal which is supplied in the molten state from other furnaces, such as the one shown in Fig. 36. When the practice requires that the steel be purified with the aid of basic slags, the hearth is lined with magnesite. Otherwise, an acid lining of silica brick and silica sand is used on the hearth.

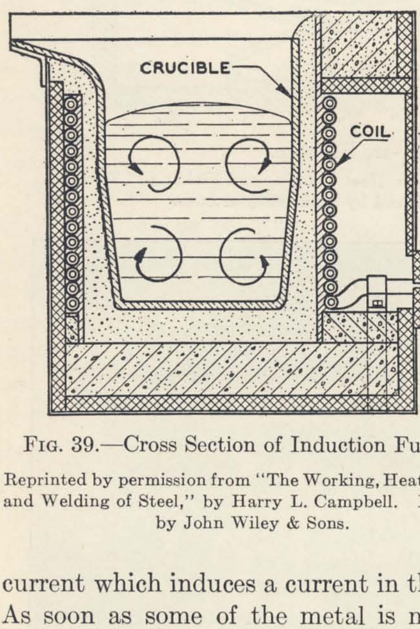

FIG. 39.—Cross Section of Induction Furnace.

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High-frequency Induction Furnace.—The high-frequency induction furnace is essentially a crucible furnace in which heat is developed by the high-frequency reversal of flux polarity within the metal charge. The construction of this furnace is shown in Fig. 39. When the furnace is in operation, water is passed through a coil of copper tubing which surrounds the crucible. This coil serves as the conductor for the high-frequency current which induces a current in the metal contained in the crucible. As soon as some of the metal is melted, a stirring action takes place which insures thorough alloying of the metal within the crucible. The capacities of induction furnaces now in use range from 100 to 8000 lb. of steel. These furnaces are operated with 960- or 1000-cycle, single-phase generators in units of 150- to 1200-kilowatt output. Six hundred kilowatts will melt about one ton of steel per hour in this type of furnace.

Steel of excellent quality can be made by any of the above methods. For economic reasons, and as a result of years of practice, steels made in this country may be classed for quality in the following order: (1) electric-furnace steel, (2) acid open-hearth steel, (3) basic open-hearth steel, and (4) Bessemer steel. So far as quantity is concerned, the basic open-

hearth furnace produces much more steel than all the other processes together. About 50 million tons of steel can be produced annually in this country, 80 per cent of which would normally be basic open-hearth steel. The electric-arc furnace, the acid open-hearth furnace, the Bessemer converter, and the high-frequency furnace—in the order named—would furnish the remaining tonnage.

93. Steel Ingots.—As a rule, all the steel made at one time in a furnace is poured from the furnace into a container known as a ladle. The ladle serves as a portable reservoir for distributing the molten steel

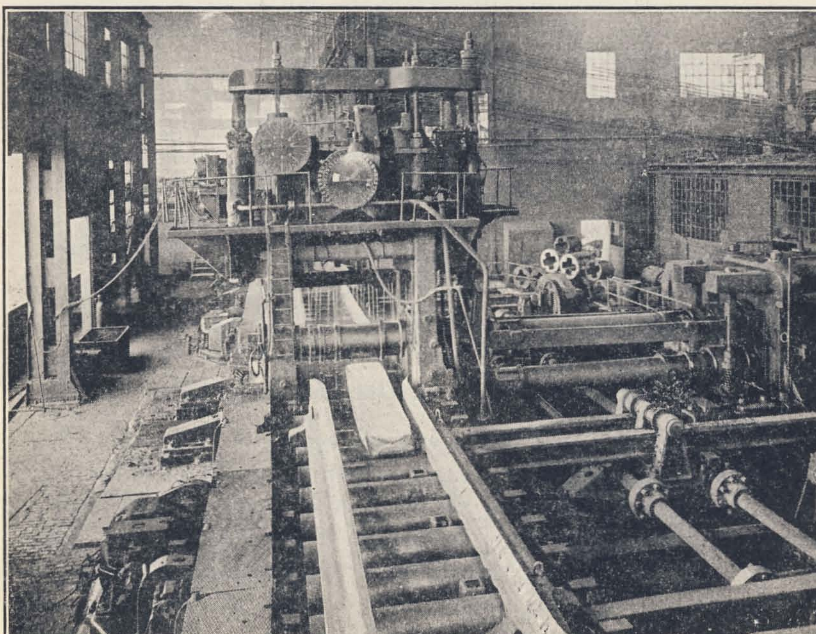

FIG. 40.—Blooming Mill.

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either to sand molds for the production of steel castings or to cast-iron molds for making steel ingots. Ingot molds are usually rectangular in shape and are tapered to facilitate the removal of the ingot. There is a considerable range in the sizes of ingots produced at different plants. In many cases the ingots are about 6 ft. high and 18 to 24 in. square, with rounded corners.

After the ingots have cooled sufficiently, they are stripped from the molds and placed in furnaces known as *soaking pits,* where they are

heated throughout to the desired rolling temperatures. From the soaking pits, the ingots are transferred to *blooming mills* in which the metal is hot-rolled to smaller sizes. After an ingot has been reduced in cross section, a portion near the top of the ingot as cast, which contains the cavity caused by the shrinkage of the metal, is cut off and discarded. The blooming mill is illustrated in Fig. 40. This mill has two large rolls mounted one above the other and with reversible direction of rotation to allow the hot metal to be passed back and forth through the rolls.

94. Non-ferrous Alloys.—The manufacture of most of the non-ferrous alloys is not difficult. Weights of the individual metals calculated to give the desired percentage composition of the alloy are melted together and then poured into sand molds to make castings or into ingot molds for subsequent forging or machining operations. It is good practice to melt first the metal with the *highest* melting point and then, for the desired alloy, to add the other metals to the liquid pool in the furnace. Care must be taken to prevent oxidation of the more active metals, such as zinc. In the manufacture of brass, for example, the copper is melted first and then the zinc is very carefully plunged beneath the surface of the molten copper to prevent its combination with the oxygen in the atmosphere at the surface of the molten pool of metal.

THE CHEMICAL COMPOSITION OF STEEL

95. Chemical Analysis.—A report of the chemical analysis gives the percentages of the elementary constituents in steel. It should be understood that these constituents are not present in the pure, elementary state in the steel, but exist in combination with iron or with one another as carbides, sulphides, etc. The purpose of a chemical analysis of steel is to determine whether the percentages of the elements are within the limits which are regarded as satisfactory for its particular requirements. The properties of steel are dependent to a large extent upon the chemical composition of the metal. Therefore, an understanding of the influence of each of the chemical elements on the properties of steel is necessary in the selection of steel for definite purposes. Only those elements which, in addition to iron, are present in all simple or plain carbon steels are included in this discussion. They are carbon, manganese, silicon, sulphur, and phosphorus.

96. *Carbon* has a greater influence on the mechanical properties of steel than any of the other elements. As the carbon is increased from 0.10 to 0.85 per cent, the tensile strength and hardness become greater, while the percentage elongation and reduction of area are lowered. This relationship of carbon content to the tensile properties and hardness

of carbon steels is indicated in Fig. 41. Steels containing more than 1.00 per cent of carbon are used only for applications requiring great hardness and little ductility. All the carbon that dissolves in liquid iron combines with a sufficient amount of iron to form the compound Fe_3C. The reactions that take place in the entire iron-carbon system are those between iron and iron carbide (Fe_3C). Strictly speaking, therefore, steel is an alloy of the constituents iron and iron carbide. The presence of this combined carbon and the fact that its solubility in iron varies widely under different conditions make possible the wide range of physical properties that can be obtained from a single piece of steel.

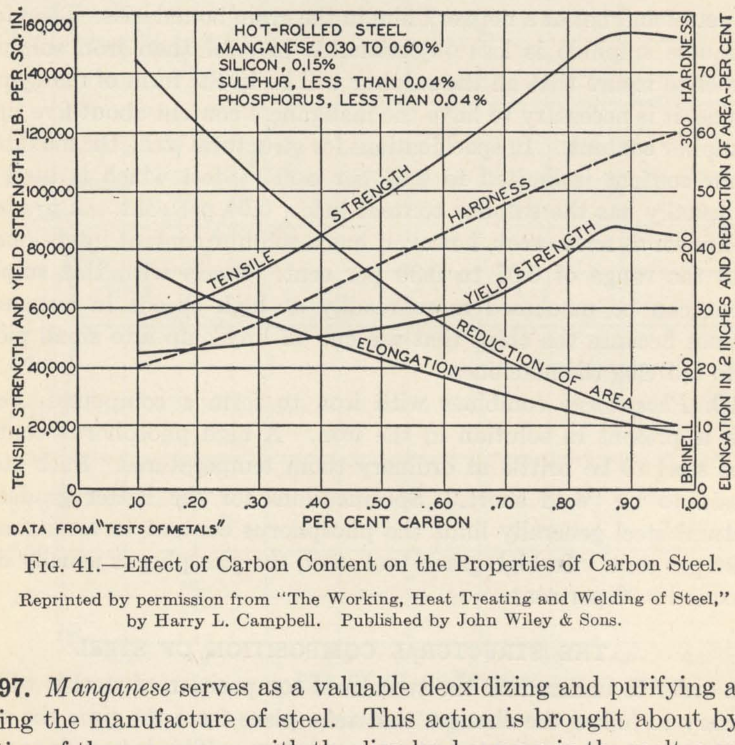

FIG. 41.—Effect of Carbon Content on the Properties of Carbon Steel.

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97. *Manganese* serves as a valuable deoxidizing and purifying agent during the manufacture of steel. This action is brought about by the uniting of the manganese with the dissolved oxygen in the molten metal, thus forming an oxide of manganese which collects in the slag. Manganese also combines with sulphur and thereby decreases the harmful effect of this element.

Manganese occurs in steel in solid solution with the iron, in chemical combination with iron and carbon, and to some extent as manganese sulphide. The manganese content of carbon steels is generally less than 1.00 per cent, and usually ranges from 0.30 to 0.80 per cent.

98. *Silicon* is particularly advantageous in the steel-making processes because of its deoxidizing and cleansing effects. The amount of silicon which remains in the finished steel usually varies from 0.05 per cent to 0.30 per cent. In these proportions, the silicon is dissolved in the iron and has no appreciable effect on the physical properties of the steel.

99. *Sulphur* occurs in steel either as iron sulphide, FeS, or as manganese sulphide, MnS. When iron sulphide is present, it forms a network at the grain boundaries of the steel. This constituent causes a lack of cohesion between the grains of the steel when it is hot worked. Steel that is brittle at forging temperatures is said to be "red short" or "hot short." Manganese sulphide collects in small round particles in the steel and not as a network film in the grain boundaries. Therefore, manganese sulphide is less objectionable in steel than iron sulphide. In order to insure that all the sulphur will be in the form of manganese sulphide, it is necessary to have the manganese content about five times the sulphur content. In specifications for structural steel, the maximum sulphur content is limited to 0.05 per cent. Steel which is used for tools usually has the sulphur content below 0.04 per cent. A grade of steel known as *screw stock*, however, has a sulphur content intentionally within the range of 0.07 to 0.30 per cent. Steels with this sulphur content can be machined more readily at high speeds in automatic machines because the chips that are cut off break up into small pieces and do not clog the machines.

100. *Phosphorus* combines with iron to form a compound, Fe_3P, which is present in solution in the iron. A high phosphorus content causes steel to be brittle at ordinary room temperatures. Such steels are said to be "cold short." Specifications for the better grades of structural steel generally limit the phosphorus content to a maximum of 0.04 per cent. In high-grade tool steel, the phosphorus usually does not exceed 0.02 per cent.

THE STRUCTURAL COMPOSITION OF STEEL

In order to understand the structural composition of steel it will be necessary to follow the changes that take place from the time the steel is molten until it is cooled to room temperature. This is best done with the aid of a *thermal equilibrium diagram* such as that shown in Fig. 42 for the iron, iron-carbide alloys.

101. A *thermal equilibrium diagram* is a graphical representation of the phases present in a system under different conditions. In a binary alloy we have two variables, temperature and composition of the alloy, that is, the percentages of the two constituents present. The equilibrium diagram may therefore be plotted on a plane using temperature as one

argument and composition as the other. In the diagram we shall get curves known as the *freezing-point curves.* These curves separate the liquid from the solid phase and give the temperature at which one or the other component freezes for a particular composition. The freezing-point curves are also correctly named *solubility* curves, since they

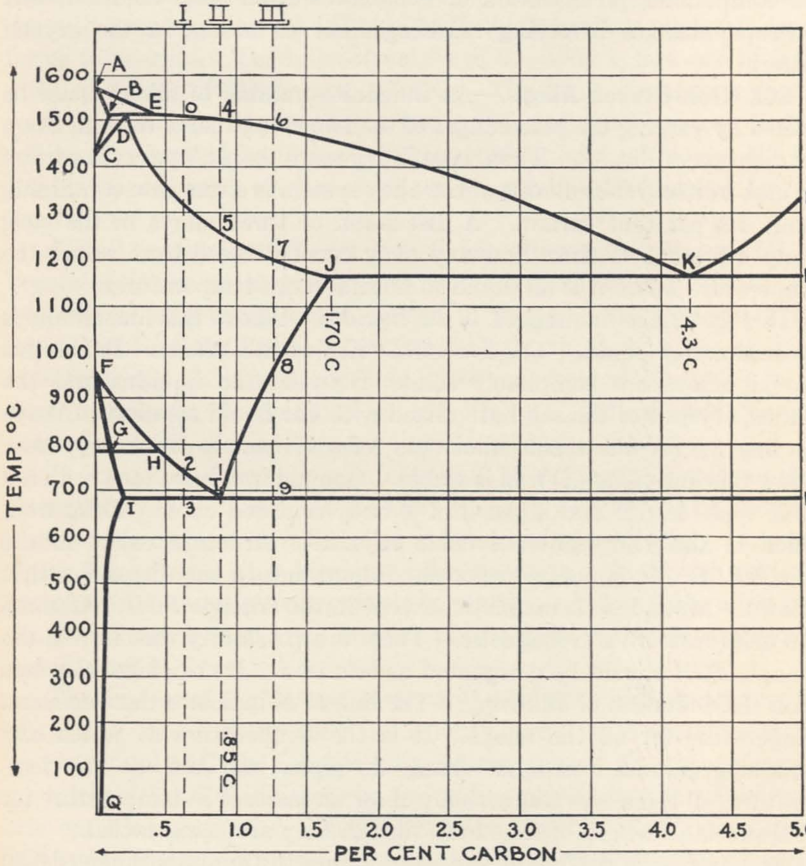


FIG. 42.—Iron-carbon Equilibrium Diagram.

represent the concentration of the solutions saturated with a given phase at a given temperature, which is a definition of solubility. It is worth while emphasizing that there is no distinction of any sort between a freezing-point curve and a solubility curve, since each represents the temperatures and compositions for the equilibrium between solid and liquid. In some alloys there exists a particular composition that has a lower freezing point than any other composition. An alloy of such a

composition is known as *the eutectic alloy*, and the point on the freezing-point curve corresponding to this composition is known as the *eutectic*. Although the freezing-point curves are the most important parts of thermal equilibrium diagrams, other phenomena are also indicated by these diagrams. Among these phenomena are the formation of chemical compounds, precipitation of substances from solid solution, and allotropic changes involving rearrangement of atoms in the crystal pattern.

102. Iron-Carbon Alloys.—An indefinite number of alloys could be formed by varying the percentages of the two constituents that make up the diagram of Fig. 42. Those containing more than 1.7 per cent carbon are cast iron and the eutectic of the alloy system is a cast iron containing about 4.3 per cent carbon. A discussion of three alloys in the steel group will serve to show how any alloy can be traced from above the temperature where it is all liquid to normal room temperature.

In Fig. 42 the line *AEKL* is the *liquidus*. Above this line all alloys are completely liquid. The line *ABDJKM* is the *solidus*. Below this line all alloys are completely solid. Between the liquidus and the solidus, crystals of the solid are mixed with the liquid solution. Above the line *FHTN* the stable allotropic form of iron is *gamma* (γ) iron. Below this line *alpha* (α) iron is stable. Gamma iron has a face-centered cubic space lattice and alpha iron is body-centered cubic. *Delta* iron, which is also body-centered cubic in lattice structure exists in the area *AEDC*. It is not of particular importance in the discussion that follows. Alpha iron is magnetic, except in the triangle *FGH*. Gamma and delta iron are non-magnetic. There is a possibility that iron in the triangle *FGH* should be designated as *beta* iron. Its existence depends upon the definition of allotropy. The line *ITN* indicates the *recalescent* temperature for all the alloys. It is the temperature at which any remaining gamma iron must change to alpha iron and, at this temperature, all the alloys will actually show an increase in temperature for an appreciable length of time even though they are being cooled.

The process of cooling of any alloy within the analysis range of 0.50 to 0.85 per cent carbon is illustrated by alloy I. Above point 0 the alloy is entirely liquid. At 0 *austenite* begins to freeze. Austenite is a solid solution of iron carbide in *gamma* iron and may contain any amount of carbon up to 1.7 per cent at 1150° C. Gamma iron is the stable allotropic form of iron above the upper critical points. Between 0 and 1 austenite freezes, and austenite then continues to exist between points 1 and 2. At 2 *ferrite* begins to form in separate crystals from the austenite. Ferrite is commercially pure *alpha* iron, and alpha iron is the stable allotropic form of iron from *FHTN* to below 0° C.

Between points 2 and 3 ferrite separates, together with a small amount of iron-carbide in solid solution as indicated by the solubility line *FIQ*. The composition of the austenite varies along the line 2-*T* to *T*. *Pearlite* is a mechanical mixture of alpha iron and iron carbide, containing about 0.85 per cent C. It can be seen from the diagram that point *T* would satisfy the definition of pearlite if the temperature dropped even one degree. Hence, at *T* the remaining austenite transforms to pearlite. The microstructure of the alloy is now one of intermingled grains of ferrite and pearlite. The same structure exists at room temperature except that a few small grains of free iron carbide will have separated from that small amount in solid solution in the ferrite as necessitated by the decrease in solubility indicated by the line *IQ*.

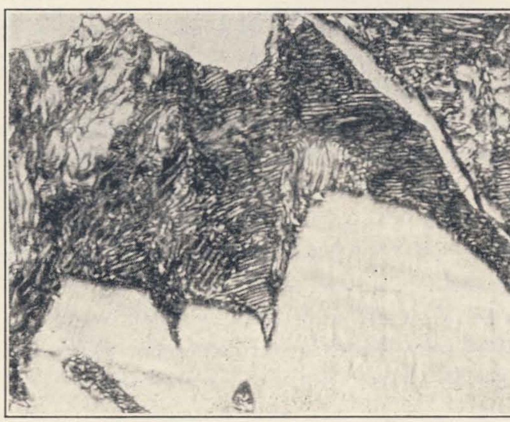
A steel containing 0.85 per cent C has a lower temperature for the beginning of the allotropic changes than any other alloy of the system. To indicate this condition of change in the solid state, steels of this carbon content are known as *eutectoid* steels, those with less as hypo-eutectoid, and those with more as hyper-eutectoid steels; much in the same manner as the designations eutectic, etc., indicate relative temperatures of the change from the liquid to the solid state.

The process of cooling a eutectoid (0.85 per cent C) steel is illustrated by alloy II. Above 4 the alloy is entirely liquid. At 4 austenite begins to freeze and at 5 the alloy is solid and is completely austenite. From 5 to *T* the alloy remains solid austenite. At *T* the austenite transforms at constant temperature to pearlite. Below *T* the alloy is all pearlite except for the small amount of iron carbide that separates as it did in alloy I.

The process of cooling any hyper-eutectoid steel is illustrated by the alloy III. Above 6 the alloy is entirely liquid. At 6 austenite begins to freeze and at 7 the alloy is all solid austenite. As the austenite is cooled to point 8, it reaches the line *TJ*, which limits the solubility of iron carbide in austenite. Just below 8 the austenite is a supersaturated solution. Hence, iron carbide precipitates in small individual grains and the composition of the remaining austenite moves along the line *TJ* to *T*. Here it contains just the right proportions of iron and iron carbide to form pearlite and the remaining austenite transforms. Below *T* the structure consists of iron carbide and pearlite.

Iron carbide has been given the metallographic name *cementite*. Cementite is very hard and brittle whereas ferrite is soft and ductile. Pearlite is a mechanical mixture of ferrite and cementite in a definite ratio ($87\frac{1}{2}$ per cent ferrite; $12\frac{1}{2}$ per cent cementite). Its properties are, therefore, intermediate between those of ferrite and cementite. Normal

0.20 Per Cent Carbon Steel—white, ferrite—black, pearlite—100x.



0.20 Per Cent Carbon Steel—white, ferrite—laminated grains, pearlite—1000x.

1.50 Per Cent Carbon Steel—laminated grains, pearlite—small angular white grains, cementite—1000x.

FIG. 43.—Constituents of Slowly Cooled Steel.

pearlite has a tensile strength of about 125,000 lb. per sq. in. and an elongation of 10 per cent.

A better appreciation of these structural constituents of steel may be had from a study of the photomicrographs of Fig. 43. The legends contain the essential descriptions of the structures.

MECHANICAL TREATMENT

103. Methods of Shaping Metals.—There are three general methods of forming metals to the shapes required of useful products. They are (*a*) casting, (*b*) mechanical working, either hot or cold, and (*c*) machining. The use of welding to join shapes obtained by the above methods into finished products may be considered as a special case of combining parts obtained by those methods. Machining is not distinctly a metallurgical process. Nor are we concerned at this time with the casting process, except to note the difference between the structure and properties of the cast metal product and that which has been obtained by mechanical work. Some shapes, on account of their intricate design, are necessarily made by casting. In general, if we consider alloys whose mechanical properties can be improved by heat treatment, well-made and properly heat-treated castings possess mechanical properties equal to forgings (mechanically-shaped pieces) of the same material, and centrifugal castings may be produced in which the properties may even be superior to those of similar forgings. Generally, however, castings do not have the strength or ductility of forgings.

104. Benefits of Mechanical Working.—Mechanical shaping improves the quality of the metal by forcing its particles into more intimate contact, closing up cavities, and by refining its crystalline structure, and so has important functions aside from the mere reduction to form and size. The change in properties that may be attributed to the process of mechanical working is a marked one; for the strength, ductility, and hardness are all affected. Of these properties, the strength is always increased by the working, the hardness may or may not be markedly increased, whereas the ductility may be either increased or decreased, depending on the conditions of the working. The amount of change in each of these properties for a given metal of a certain chemical composition is affected by the amount of work done and by the temperature at which the working is carried on.

105. The Two Temperature Ranges of Working.—In considering the mechanical treatment of steel, or of any metal, the first distinction to be made is that of hot- and cold-working. These terms, hot and cold,

as they are commonly used, are indefinite or relative; but, as applied to the mechanical working of steel, they are separated by a sharp and well-defined line, in any particular class of steel at least. This line is described by the temperature at which rapid grain growth occurs; and rapid grain growth, being a physical phenomenon similar to fusion or boiling, begins at a definite temperature for any single substance, if other conditions are constant. Since grain deformation and grain growth form the basis upon which the division is made, a study of metallography is necessary to a thorough understanding of this subject. The following brief discussion is intended merely to serve as an introduction to the subject and as a means that will, at least, lead the student to a better appreciation of the effects of working the metal in these two temperature ranges.

106. Cold-working.—Let it be assumed that a certain piece of low or medium carbon steel is to be worked at ordinary room, or atmospheric, temperature. If this steel has been previously subjected to hot-working, as ordinarily would be the case, it will exhibit certain mechanical properties, and will have a certain structure. A photomicrograph of the metal will show that it is made up of two constituents, the white areas representing grains of pure iron, or ferrite, and the dark areas grains of pearlite. If, now, the piece of steel is mechanically worked, that is hammered, rolled, drawn, or otherwise permanently deformed, its mechanical properties are changed, and its structure also becomes different. A photomicrograph will show very much smaller grains, the size depending on the amount of mechanical working, and elongation of the grains in the direction in which the metal was worked. If tested immediately after cold-working, the tensile strength and hardness will now be much higher than before the steel was worked, whereas the ductility, as represented by the elongation and reduction of area, will be decreased. The original grains have been broken up into smaller grains. The metal is stronger, harder, and less ductile, and is in a *strained condition.* Now, if the metal is heated to a temperature of 150° C. for a day or two, it will show a higher proportional limit and the elastic limit will be much higher than before the metal was worked. This phenomenon can be explained by assuming that the disorganized atoms, by virtue of their vibratory motion, are able to rearrange themselves to some extent even at ordinary temperatures. This ability, of course, would be increased by increasing the energy of the vibrations, that is, by increasing the temperature of the piece. Up to 300° C., however, the microscope reveals no change in the structure; but between 300° C. and 520° C., a gradual change in the strained grains can be

observed. Above 520° C., the change in structure takes place more rapidly, until, at 600° C., what appear to be new grains form in a very short time, and the mechanical properties, if the steel is of low carbon content, approach the values they had in the beginning. This statement does not apply to high carbon steel, because the change affects only the ferrite grains, the pearlite grains retaining their elongated form. These new ferrite grains have almost the same form as the original grains, but are, at first, smaller. If the steel is held at the recrystallization temperature for some time, the grains may grow larger, if other conditions are favorable to growth. This granulation of the ferrite is due to the fact that the original grains are broken down, and that the fragments form centers, or nuclei, for the growth of the new grains. It should now be evident that the change in properties resulting from cold working is due to the strained condition of the grains, and that, to produce a strained condition in the grains, the working must be done at a temperature below that where recrystallization or grain growth takes place rapidly.

107. Hot-working.—Because steel represents an aggregate, not a perfectly homogeneous material, annealing at 600° C. does not remove all the effects of the cold-working. Thus, the pearlite, unless the steel is held at the annealing temperature for a considerable period of time, undergoes little change below 600° C., so the grains of pearlite remain in a strained condition at that temperature. To bring about a complete change in the structure and relieve all strains, the steel must be heated to some temperature well above 700° C. The exact temperature depends upon the carbon content of the steel, and, because of the nature of the changes that take place, this temperature is called the critical temperature, or the thermal critical point. At this point the metal undergoes a complete transformation; it loses its magnetism and elasticity; it becomes weaker, but more ductile; it becomes a solid solution of iron carbide in iron; and its crystalline form changes from that of alpha to that of gamma iron. Heating above this temperature, therefore, gives rise to an entirely new structure, and removes the strains from all the grains. Furthermore, if the temperature be raised to a point just above this critical, the maximum refinement of grain will be obtained; for no matter how large the grains of ferrite and pearlite are, the grains of austenite will be of minimum size, because the transformation takes place at the lowest temperature at which austenite forms, a condition unfavorable to grain growth. If the steel be heated to a higher temperature, no further change in crystalline form takes place; but the steel becomes weaker and more plastic and the grains

grow in size, apparently devouring each other in the process. And, if the steel be mechanically worked, the crystals are deformed as in cold-working. The deformation is only temporary, however, for, owing to the greater atomic energy, the crystal fragments will at once form new grains, which in turn will grow rapidly to a definite size, corresponding to the temperature. Also, if the steel is now cooled normally, the size of the grains of the gamma iron determine the size of the grains of alpha iron. Thus, it will be seen that working in this range may result in considerable grain refinement, the extent of which depends on the size of the section, the amount of work done on a piece, and the temperature at which the working is stopped, i.e., *the finishing temperature.* This grain refinement is one of the factors that determine the quality of the metal, for small grains offer more resistance to deformation than large ones and impart greater strength and toughness to the material. Since all strains produced mechanically at temperatures above the critical points of steel are immediately and completely removed by recrystallization, all working done in the range between these and the fusion points is to be considered *hot-working.*

From what has already been said, it should be evident that, after hot-working, if the metal is heated above the finishing temperature, the grain refinement obtained by the working may be partly or entirely destroyed, depending upon how far above this temperature the second heating is carried. This fact should always be kept in mind, and should be considered most seriously in all cases where steel is to receive little or no working after reheating, as is often the case in fabrication by hot-finishing operations. On the other hand, the reheating may be done so that the grain will be very fine without much working, for reheating to a temperature just above the critical will, in itself, refine the grain.

In distinguishing between hot- and cold-working, therefore, we may say that cold-working is done at temperatures below the annealing temperature of the metal, whereas hot-working is carried out at temperatures above the annealing temperature. The working temperatures for forging or other hot-working of carbon steel are shown on Fig. 44. Note that the proper finishing temperature is about 800° C. In hot-working alloy steels, the effect of the alloying elements on the critical range of the steels must be taken into account and the working temperature either raised or lowered accordingly.

108. Hot-working of Non-ferrous Alloys.—Many non-ferrous metals and alloys are also wrought by hot-working. Among the more important of these are aluminum and the wrought-aluminum alloys; many of the bronzes; brass; some of the magnesium alloys; and Monel

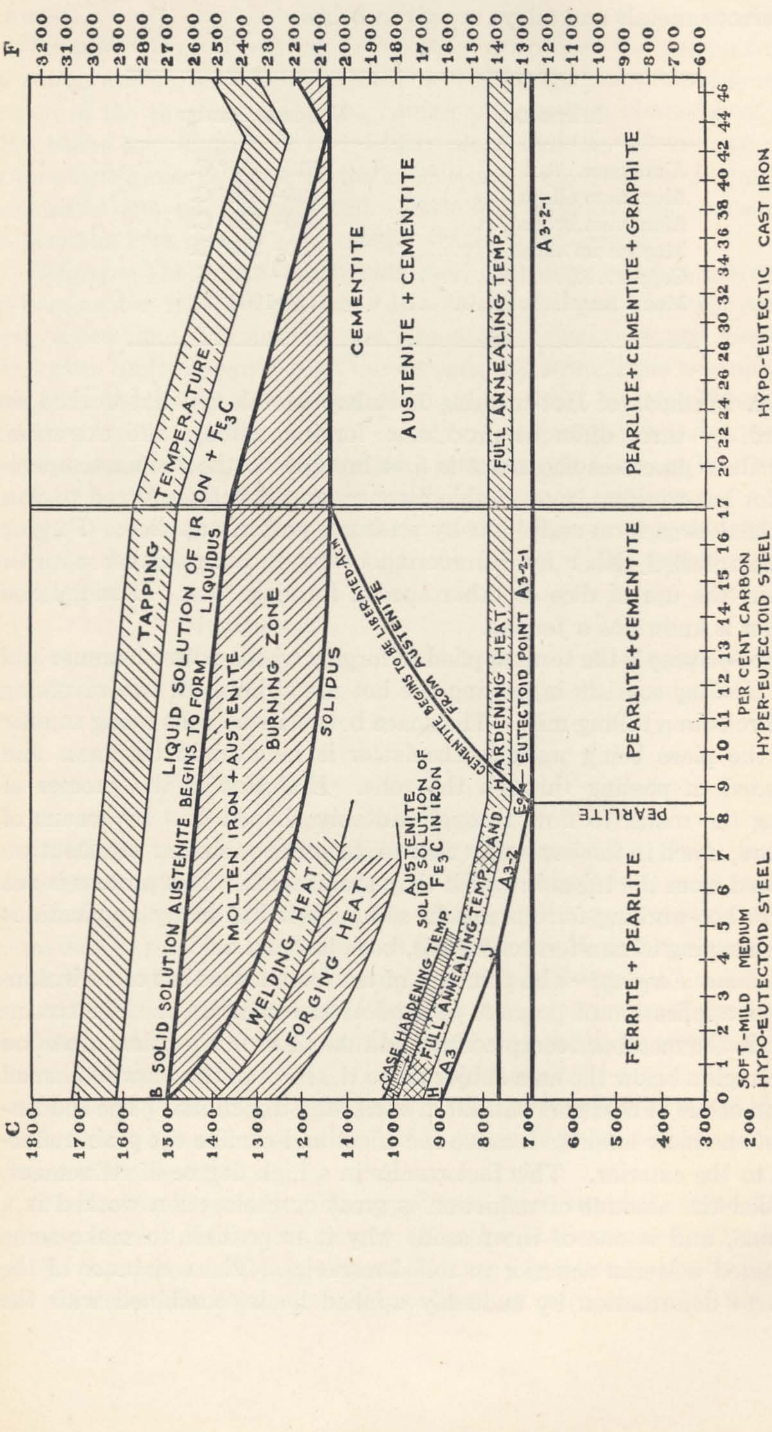


FIG. 44.—Iron-carbon Diagram with Useful Working Temperatures.

metal, which is a nickel-copper alloy. Forging temperatures for some non-ferrous metals and alloys are given below:

Material	Forging Range
Aluminum	510– 315° C.
Aluminum alloys	625– 500° C.
Aluminum bronze	920– 880° C.
Magnesium alloys	450– 315° C.
Copper	850– 750° C.
Monel metal	1170–1000° C.

109. Methods of Hot-working Metals.—Metals are hot-worked, in general, by three different processes: forging, rolling, and extrusion. In all these processes the metal is first brought to the proper temperature for hot-working in a suitable furnace, and it is then forced to flow into the desired form and shape by pressure, properly applied. Forging is accomplished either by hammering or by pressing, either with or without the use of dies or other special forming tools. The finished product is known as a *forging*.

Drop-forging is the term applied to forging with a power hammer and dies. *Rolling* consists in passing the hot metal between two revolving metal rolls in a rolling mill. The space between the rolls being smaller than the piece being worked, the latter is reduced in thickness and elongated in passing through the rolls. *Extrusion* is the process of forcing the metal to flow through suitably shaped dies by means of pressure, much in the same way that tooth paste or similar products are extruded from the tubes in which they are packed. This process is not used in hot-working ferrous metals although it has many applications in the shaping of non-ferrous metals, both hot and cold.

Hammer Forging.—The principle of the hammer is that of an instantaneous application of pressure to a relatively small area. The strains set up in the metal are compressive and take place in a vertical direction in the region below the area subjected to the force of the blow. A small portion of the blow is transmitted in horizontal directions. The suddenness of the blow tends to localize the effect and confine the grain refinement to the exterior. This fact results in a high degree of refinement, provided the amount of reduction is great or the section worked is a thin one, and is one of the reasons why it is possible to make some hammered material superior to rolled material. The resistance of the metal to deformation by suddenly applied loads, combined with the

intermittent action of the hammer, makes shaping by hammer a slow process.

Press Forging.—The press differs very much from the hammer, both in action and in the effects produced. Unlike the instantaneous application of the pressure, as in the hammer, the action of the press is so slow that a kneading of the metal takes place, and the deformation, with consequent grain refinement, instead of being confined to the surface, penetrates deep into the material. Press forging is generally considered to give the best quality that can be obtained by forging.

Rolling.—The process of shaping steel by rolling consists essentially of passing the material between two rolls revolving at the same peripheral speed and in opposite directions, i.e., clockwise and counterclockwise, and so spaced that the distance between them is somewhat less than the height of the section entering them. Under these conditions the rolls grip the piece of metal and deliver it reduced in height and increased in length in proportion to the reduction, except for a slight lateral spreading which is almost negligible in some sections.

110. Fundamental Forging Operations.—The process of shaping metal by forging may involve any one or all of the following basic operations:

Drawing out.
Upsetting.
Shaping.
Bending.
Punching, splitting, and cutting.
Welding.

(1) *Drawing out* consists of lengthening metal by blows from a hammer, by rolling it between rolls, or by pressing it in a press, usually operated by hydraulic power. The shape of the cross section of the metal may or may not be changed in the process. A square section may be made round; a round section made square or hexagonal.

(2) *Upsetting* is the reverse of drawing out. It consists of shortening the length of the piece of metal and increasing the cross section by use of the hammer or press.

(3) *Shaping* or changing the cross section of the piece of metal is also accomplished by means of either the hammer or press. This operation combines the first two.

(4) *Bending* is performed on any shaped piece of metal. One side of the piece is stretched or drawn out; the other is compressed or upset.

(5) *Punching*, splitting, and cutting are operations very similar to one another. Punching is making holes of any shape. They are

usually round, square, or elliptical, and are made by driving a punch of the proper size and section through the metal by means of blows or pressure. Splitting and cutting are accomplished by driving a chisel through the metal; splitting is usually lengthwise of the piece, and cutting, crosswise, to sever the stock.

(6) *Welding* is the uniting of two or more pieces of metal, or the two ends of a single piece (bent so as to meet), that have been heated to such a temperature that they are in a plastic or fluid state. Welding may be classified as plastic or fusion welding, depending on whether the metal is united by the application of a pressure or a blow while in a plastic condition or is united in the fluid state. Either class of welding requires a nice and contemporaneous adjustment of the heat in the parts to be welded. The surfaces must be clean.

HEAT TREATMENT

Pure metals are not affected by heat treatments other than annealing treatments designed to cause recrystallization or the relief of strained conditions caused by mechanical work. The same is true of alloys in which there is no decrease in solid solubility with decreasing temperature—as in gold-silver alloys. All examples of appreciable change in the mechanical properties of alloys, brought about by heat treatments, seem to be caused by a change in the solubility of one of the elements of the alloy as the temperature is changed, or by a marked reduction in grain size. A typical example of gradual change in solubility is that of the copper-aluminum alloys. An abrupt change in solubility may be caused by a change in the allotropic form of the solvent as the temperature is changed. Steel is an example of this type. In either case, the object of heat treatment is to assist or interfere with the natural laws of solubility and to produce grain refinement.

Metals fail when adjacent grains slip by each other and when single grains are broken and the fragments slide along crystallographic planes. The resistance that a metal offers to both these forms of slip is a measure of its strength. The *slip interference* theory of the hardening of metals is formulated on the assumption that particles of a *critical size* dispersed along these grain boundaries and crystallographic planes will act to prevent slip, as does sand on ice, and will, therefore, increase the strength and hardness of the metal.

111. Heat Treatment of Duralumin.—The aluminum-copper alloy, duralumin, can be used to illustrate the application of this theory. The thermal equilibrium diagram for this alloy system shown in Fig. 45 indicates that about 5.0 per cent Cu will be dissolved in aluminum at

550° C., and that the solubility for copper decreases along the line *OB* to 1.5 per cent at room temperature. Since duralumin contains 4 per cent Cu, the entire copper content will be dissolved in the aluminum if the alloy is heated to 550° C. If the alloy is allowed to cool slowly it will become supersaturated at some point *X* about 500° C. The chemical compound $CuAl_2$ will separate out and form individual grains and, at room temperature, the structure will consist of relatively large grains of aluminum, with 1.5 per cent Cu in solid solution, and of grains of the compound $CuAl_2$. The tensile strength of the alloy will be about 26,000 lb. per sq. in. and the elongation about 20 per cent. Now if the alloy is reheated to 550° C., the copper will go back into solution as required by the equilibrium diagram. If it is then quickly immersed in cold water and brought to room temperature, the copper will not have had time to precipitate and the alloy will consist of grains of supersaturated aluminum. The properties of the alloy will not be much different from the way they were before.

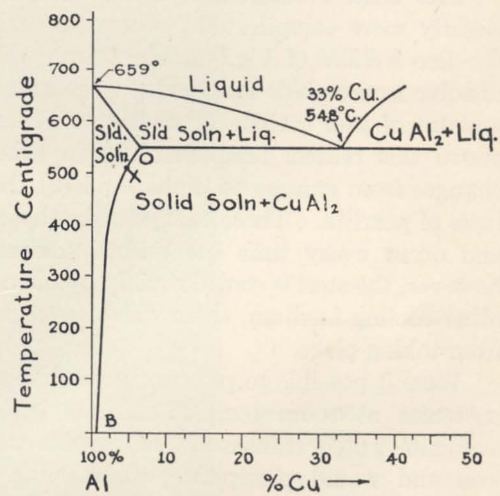


FIG. 45.—Copper-aluminum Equilibrium Diagram.

However, supersaturated solutions, liquid or solid, are notoriously unstable. $CuAl_2$ particles will start to precipitate throughout the alloy. At first they will be very small—far too small to be seen even under the highest powers of the microscope. Soon, however, these particles agglomerate and reach the necessary *critical* size. This process is known as "aging." It will take place in a period of days at room temperature, or in a few minutes if sufficient kinetic energy is imparted to the atoms by raising the temperature of the alloy to some 100° C. When this critical particle size has been reached by a sufficient number of these groups of $CuAl_2$ particles, the alloy will possess a tensile strength of about 58,000 lb. per sq. in., and the elongation may have dropped to 16–17 per cent.

If further aging is permitted by holding the alloy at 100° C., or raising the temperature to 200° C., further agglomeration will take place, the critical particle size will be exceeded, and the material will

lose this extra strength progressively until the original properties are again approached.

It should be noted that duralumin contains small percentages of magnesium and manganese. These elements play an important part in the hardening of the alloy but their effect has not been discussed to avoid complication of the discussion of the fundamental idea of the hardening of alloys.

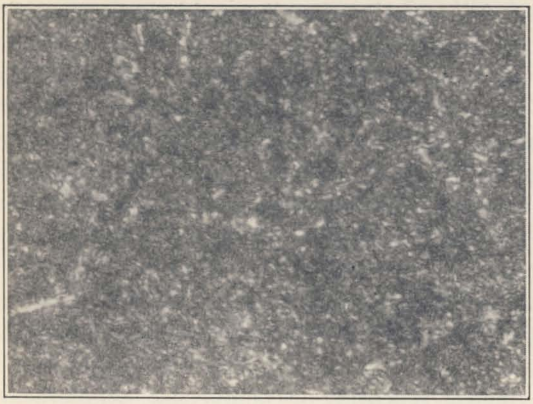
112. Heat Treatment of Steel.—The heat treatment of steel is but slightly more complicated. Above the critical temperature shown by the line *FHTN* of Fig. 42, alpha iron which has very little power to dissolve iron carbide transforms to gamma iron, which can hold a large amount of iron carbide in solution. When steel is cooled *slowly* from above this critical temperature, two things take place: (1) the iron changes from gamma to alpha, and (2) the carbide precipitates in the form of pearlite. These changes, like those in duralumin, are reversible and occur every time the critical temperature range is passed. If, however, the steel is cooled rapidly by quenching it in water, oil, or some other cooling medium, there will be a tendency to prevent both changes from taking place.

Were it possible to prevent these changes, the steel would consist of austenite at room temperature. If left undisturbed, however, the austenite would transform, the carbide would not be soluble in alpha iron and would precipitate, and, consequently, the material would "age." This aging would undoubtedly be speeded up by any amount of heating below the critical range.

In practice, however, it is not possible to cool with sufficient speed to prevent these changes fully, and the steel is already "aged" and fully hardened when it is taken from the quenching bath. Though some small amount of austenite may be retained, the steel is composed very largely of grains of alpha iron in which there is a submicroscopic dispersion of particles of iron carbide. Such a structure is very hard and brittle and is called *martensite.* Steel with a martensitic structure is of little use because of its brittleness.

113. Microstructure of Heat-treated Steel.—When martensite is heated to some temperature not in excess of about 400° C., however, sufficient agglomeration of carbide particles will take place so that the critical particle size will be exceeded and the material will be somewhat softer and tougher. The microscopic structure will be different from that of martensite. It is called *troostite.* Steel with a troostitic structure combines a high degree of hardness with some toughness and is useful for tools.

Further heating permits still more agglomeration of the carbide



0.90 Per Cent Carbon Steel—water quenched, 830° C.—tempered, 650° C.—Structure, sorbite—1000x.

Section of case—carburized steel—white, undeveloped martensite—black rosettes, troostite—1000x.

0.60 Per Cent Carbon Steel—water quenched, 850° C.—not tempered—angular needle-like structure, martensite—1000x.

FIG. 46.—Constituents of Heat-treated Steel.

particles until, at about 600° C., another metallographic structure called *sorbite* is developed. Sorbite will then exist, with still further heating, until the critical range is reached. In sorbite, the carbide particles have grown so large that they can be seen with the microscope. Sorbitic steels are not as hard as martensitic or even troostitic steels, but they are harder than slowly cooled steels whose structure consists of pearlite and ferrite. They are very useful for all engineering applications requiring toughness. Photomicrographs of these heat-treated structures are shown in Fig. 46.

A summary of the different sets of mechanical properties that can be obtained from the same piece of a 0.45 per cent C steel by heat treatments is shown in Table I. Any desired properties within these limits can be obtained by changing the reheating or "tempering" temperature.

TABLE I

PHYSICAL PROPERTIES—0.45 PER CENT CARBON STEEL

Condition	Structure	Brinell Hardness	Tensile Strength lb./sq. in.	Elongation % in 2 in.
Slowly cooled............	Pearlite and Ferrite	160	80,000	20
Water quenched..........	Martensite	550	230,000	4
Water quenched and reheated to 400° C........	Troostite	260	125,000	15
Water quenched and reheated to 600° C........	Sorbite	220	105,000	20

114. Definitions.—The following definitions of heat-treating terms will be found essential for practical application of the theories of heat treatment:

Heat Treatment.—An operation or combination of operations involving the heating and cooling of a metal or an alloy in the solid state for the purpose of obtaining certain desirable conditions or properties. Heating and cooling for the sole purpose of mechanical working are excluded from the meaning of this definition.

Quenching.—Rapid cooling by immersion. Immersion may be in liquids, gases, or solids.

Hardening.—Heating to and quenching certain iron-base alloys from a temperature either within or above the critical temperature range.

Annealing.—Annealing is a heating and cooling operation of a material in the solid state. Annealing usually implies a relatively slow cooling. The purpose of annealing may be: (1) to remove stresses, (2) to induce softness, (3) to refine the crystalline structure, or (4) to

produce a definite microstructure. For iron-base alloys true annealing requires heating above the critical temperature range, holding above that range for a proper period of time, followed by slow cooling through the critical range.

Normalizing.—Heating iron-base alloys to above the critical range, followed by cooling fairly rapidly to below that range, usually in still air.

Tempering (also termed *Drawing*).—Reheating iron-base alloys *after hardening* to some temperature below the critical temperature range, followed by any desired rate of cooling.

Surface Hardening of Steel.—Bearings, wrist pins, and many other articles are subjected to service that requires a very hard surface, or *case*, to resist wear and abrasion, and a tough backing, or *core*, to enable the case to withstand shock. Such articles may be prepared by (1) case carburizing, (2) nitriding, or (3) cyaniding. *Case carburizing* is accomplished by heating above the critical range in close contact with solid, liquid, or gaseous carbonaceous materials. Carbon diffuses into the surface layers of the solid steel and produces a combination steel that is high in carbon at the surface and of the original low carbon content in the core. The material may then be given the proper heat treatment, corresponding to the carbon content, to produce a hard case and a tough core. *Nitriding* is accomplished by heating specially prepared steels below the critical temperature in the presence of ammonia. The ammonia dissociates into nitrogen and hydrogen, and the nitrogen combines with the iron near the surface to produce iron nitrides that are extremely hard. Nitriding has the advantages that the case produced is much harder than the one obtained by carburizing and that subsequent heat treatment is not required. However, it takes a much longer time and is more costly. *Cyaniding* consists of heating steel above its critical range in a bath of molten potassium or other cyanide, followed by quenching. It produces a hard but relatively thin case.

TESTING METALS

One of the greatest problems in engineering work is the determination of the best distribution and selection of material to give the required strength to a structure, with bulk and weight as low as is consistent with safety. Tests of various classes of materials are made to give the designer the information necessary to enable him to use the proper materials to the best advantage. The method which gives the most direct information is a test to destruction of a completed structure. A test of this type is usually very costly and seldom carried out, unless it is necessary to have complete information, as in a test for the accuracy life of a gun. However, a proof test is often used, which consists of

subjecting the completed article to a load slightly greater than that which it will be required to withstand in normal use.

Numerous tests have been devised to obtain information relative to the strength and properties of metals. The proper application of testing demands that those tests, and only those, that will give necessary and useful information, be performed. In certain cases a rough test for hardness with a machinist's file may be sufficient. In others the most complicated laboratory methods may be necessary.

115. Methods of Testing.—The most common tests available are:

(*a*) *Physical* tests to determine hardness, ductility, toughness, tensile, impact, and fatigue strengths.

(*b*) *Chemical* tests to determine the percentage of each element present in the metal, in order that proper heat treatments may be prescribed to produce the desired physical properties.

(*c*) *Metallographic* tests to determine the structural composition as shown at low and high magnification and by X-ray diffraction methods.

(*d*) *Radiographic* tests to determine the soundness of castings and welded joints as indicated by means of X-rays and gamma rays.

The ultimate composition (percentage of elements) of a metal is ascertained by standard chemical laboratory procedure. Determinations are made only for those elements whose presence in a particular quantity are essential to proper functioning of the material and for those elements whose presence is known to be harmful.

116. Metallographic Testing.—The structural composition of a metal is not fixed by its chemical composition. The nature of the crystals, their relative sizes and shapes, the manner in which they are arranged within the metal, and the presence and nature of mechanically entrapped impurities that have an important bearing on the quality of the metal are brought to light by metallographic examination. Metallography includes:

(*a*) *Macro-examination*, for gross characteristics such as the general crystal structure, seams, and marked segregation of the constituents. It consists in visual observation of a prepared specimen without the aid of lenses, or with optical equipment up to magnifications of 15 diameters.

(*b*) *Micro-examination*, for details of the structural arrangement of the metal and non-metallic particles entrapped during solidification. As the name implies, it consists of microscopic examination of a highly polished specimen at magnifications from 15 diameters (15x) to the limit of optical equipment—for practical purposes about 4000 diameters (4000x).

Specimens for macro- and micro-examination may be examined as

polished. More frequently, however, they are dipped in solutions, such as nitric acid in alcohol, before examination. Such etching solutions attack some constituents of the metal in preference to others and dissolve minute quantities of the material in the grain boundaries, thereby making possible a more complete study of the specimen. Photographs are usually made showing the characteristic structures of the specimen under examination. They serve as a record of the examination, and are called photomicrographs.

(c) *X-ray diffraction* studies, to determine the space lattice arrangement of the elementary crystals and to detect conditions of atomic strains. These studies are made by permitting a specimen of the metal to diffract a beam of X-rays, the diffracted rays being registered on photographic plates.

117. Radiographic Testing.—Because of their very short wave lengths, X-rays penetrate materials opaque to ordinary light; but even X-rays are absorbed by heavy material, such as lead, very much as light is absorbed by fog. If X-rays are passed through metal that contains cracks, cavities, slag inclusions, or metal segregations, the rays that pass through the defects are absorbed to a less extent than the rays that pass through the adjacent sound metal. A photographic film, placed to intercept the rays after passing through defective metal, will show spots and areas that define and locate existing internal defects. The method thus is similar to the process used by the medical profession to determine bone fracture and other internal conditions of the human body. Radiographic testing is used (1) for the development of casting technique in the foundry, (2) for the development of welding technique, and (3) for the final inspection of products manufactured by casting or by welding. In the final inspection of products manufactured by casting or by welding, the advantage of the X-ray test in searching for hidden defects without injuring the finished product is obvious. Cracks, gas cavities, and similar internal structural weaknesses in a material subject to high stress in service would be extremely dangerous. Examples of this in the modern antiaircraft gun mount are (1) of a casting, the trunnions on the cradle, and (2) of a welded structure, the pedestal.

118. The Physical Testing of Metals.—The chemical composition of a metal, as well as the heat treatment and mechanical working to which it has been subjected, control its physical properties. The quality of a metal is usually established on the basis of tensile properties and hardness. Other tests, however, can be used in determining its strength under compression, shear, or torsional loading. Furthermore, specimens may be subjected to suddenly applied loads as in impact testing, or to many repetitions of loading as in fatigue testing.

The selection and preparation of the material for test specimens

should receive careful attention. In all cases, the metal in the test specimen must have had the same thermal and mechanical treatments as the item which it represents. A record is usually kept of the exact location from which the material for the specimen was

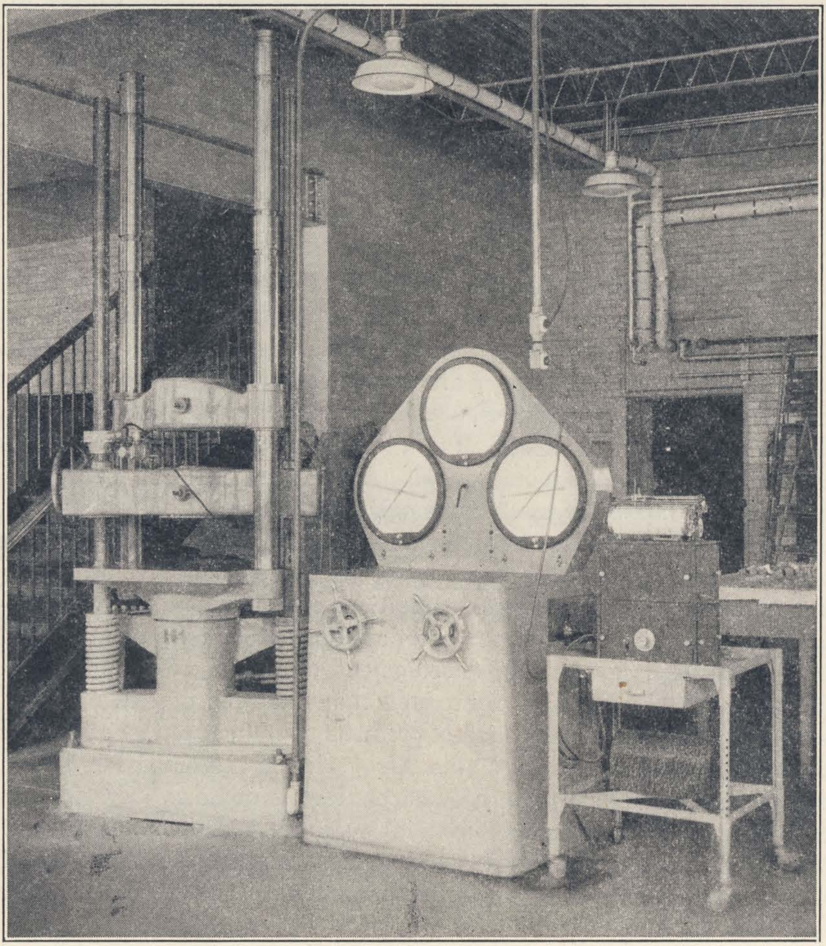


FIG. 47.—Universal Testing Machine.

obtained. It is also important that all test specimens have the form and dimensions prescribed in standard specifications. The tensile test requires the gradual application of axial loads to standard test specimens until rupture occurs. A testing machine is shown in Fig. 47. The tensile test specimen is gripped in the pulling head and in the top head of the machine. During the test, the load at any instant is indicated by the position of the dials. From these loads, the stress-strain

diagram can be plotted and the physical properties defined above may be determined.

119. Hardness Measurements.—The most common methods for measuring the hardness of metals are those employing the Brinell testing machine, the Rockwell hardness tester, and the Shore scleroscope.

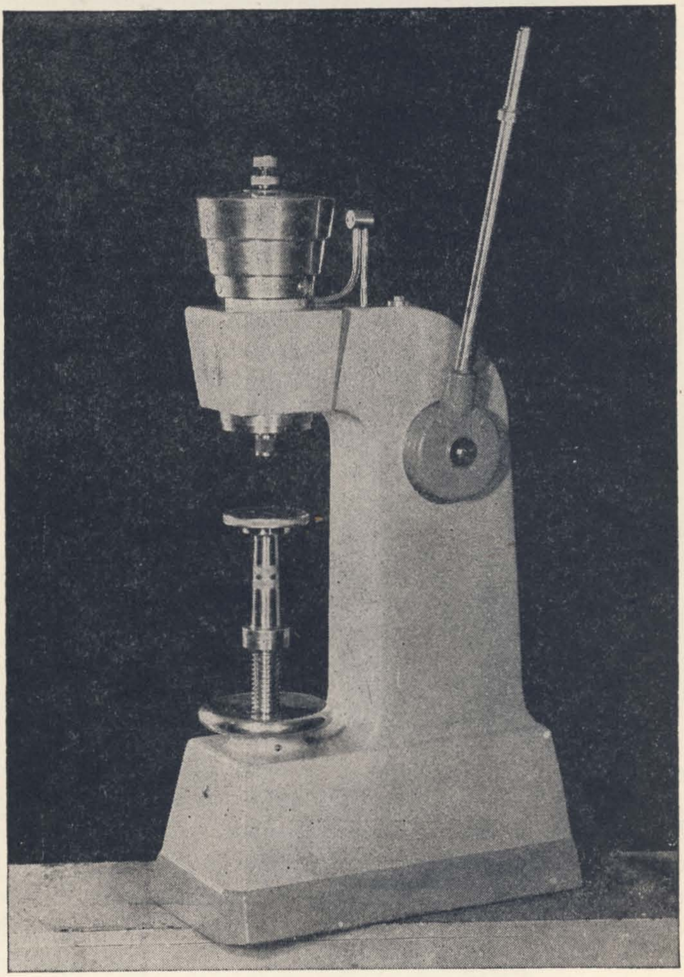


Fig. 48.—Brinell Hardness-testing Machine.

Each of these will be described. It is necessary to have the surfaces of the work smooth and free from scale and decarburized metal before making a hardness test. It is also important that the work be mounted in a horizontal position in the testing apparatus.

Brinell Test.—In the Brinell test, a hardened steel ball 10 mm. in

diameter is forced into the sample, under a load of 3000 kilograms, for a period of 30 seconds. The diameter of the indentation formed on the sample is measured in millimeters with the aid of a microscope. The Brinell hardness number is the quotient secured by dividing the applied load in kilograms by the area of the impression in square millimeters. Brinell hardness numbers with corresponding diameters of impressions are given in Table II. A Brinell hardness-testing machine is shown in Fig. 48. This instrument is most widely used for measuring the hardness of metals.

Rockwell Test.—The Rockwell test serves to measure hardness by determining, under an increment of load, the increment of depth of penetration of a steel ball or diamond cone into the material being tested. A preliminary load of 10 kilograms is first applied to a hardened steel ball 1/16 in. in diameter against the surface being tested, and then a major load of 100 kilograms is used. The Rockwell hardness readings are based on the depth to which the major load forces the steel ball below the depth to which it was impressed by the preliminary load. In the testing of very hard metals, a 120° diamond cone is used with a major load of 150 kilograms. Where shallow penetration is desired, as in testing high surface hardness, a spheroconical diamond penetrator is used under a minor load of 3 kilograms and major loads of 15, 30, or 45 kilograms. A Rockwell hardness tester is illustrated in Fig. 49. This tester is much used for plant control and inspection purposes.

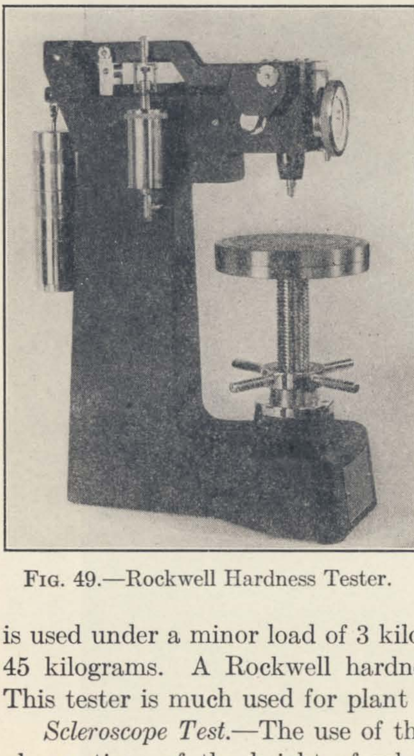


FIG. 49.—Rockwell Hardness Tester.

Scleroscope Test.—The use of the Shore scleroscope is dependent on observations of the height of rebound of a diamond-tipped hammer which is allowed to fall through a fixed distance upon the polished surface of the material being tested. The hammer travels within a glass tube which is supported in a vertical position.

The Vickers hardness tester employs a square-based diamond pyramid. In other respects it is similar in principle to the Brinell machine. A choice of loads is permitted and the distance between opposite corners

of the impression is read with a graduated microscope permanently attached to the machine. The Vickers machine is valuable for testing very hard surfaces.

Although there are no quantitative relations between hardness values and tensile strengths which apply to all steels, information giving the approximate relations between hardness numbers and tensile strengths is often useful. The comparative values of hardness and strength presented in Table II represent average conditions for heat-treated structural alloy steels.

TABLE II

HARDNESS CONVERSION TABLE FOR ALLOY STRUCTURAL STEELS *

Brinell Test Diameter of Impression Millimeters with 3000-kg. Load and 10-mm. Ball	Brinell Hardness Numbers	Rockwell Hardness Numbers "C" Scale 150-kg. Load and 120° Cone	Rockwell Hardness Numbers "B" Scale 100-kg. Load and 1/16-in. Ball	Shore Scleroscope Hardness Numbers	Approximate Tensile Strength in Units of 1000 Pounds per Square Inch
2.20	780	68	....	96	
2.30	712	65	....	92	354
2.40	653	62	....	86	329
2.50	601	58	....	81	305
2.60	555	55	....	75	284
2.70	514	51	....	71	263
2.80	477	48	....	66	242
2.90	444	46	....	62	221
3.00	415	43	....	58	202
3.10	388	41	....	54	185
3.20	363	38	....	51	171
3.30	341	36	....	48	159
3.40	321	34	....	45	148
3.50	302	31	....	42	139
3.60	285	29	....	40	131
3.70	269	27	....	37	124
3.80	255	25	....	35	117
3.90	241	23	99	33	112
4.00	229	21	98	32	107
4.10	217	18	96	30	103
4.20	207	16	95	29	98
4.30	197	14	93	28	95
4.40	187	12	91	27	91
4.50	179	10	89	25	87
4.60	170	8	87	24	84
4.70	163	6	85	23	81
4.80	156	4	83	23	78
4.90	149	2	81	22	76

* Data compiled by the Research and Development Department of The International Nickel Company. Reproduced by permission.

120. Impact Tests.—A measure of the toughness of a metal is indicated by the reduction of area in the tensile test and can be obtained

from tests in some form of impact-testing machine. Machines which have been devised for testing materials under conditions of impact or shock may be roughly divided into two classes: (*a*) machines for breaking the given specimen at a single blow and (*b*) repeated-impact machines for delivering a number of blows before fracturing the specimen.

The essential parts of a machine of the first class are a swinging pendulum or weight which strikes or pulls the test piece with sufficient energy to cause fracture, an anvil or block on or in which the specimen is supported, and a device for measuring the kinetic energy of the weight after it has broken the specimen. The energy lost by the weight is a relative measure of the toughness of the metal. The toughness factor thus obtained is strictly relative and must be compared with the results obtained from similar metals whose characteristics are known. Machines in the second class are the Cambridge drop-hammer type, the Eden-Foster, and vibratory spring testers.

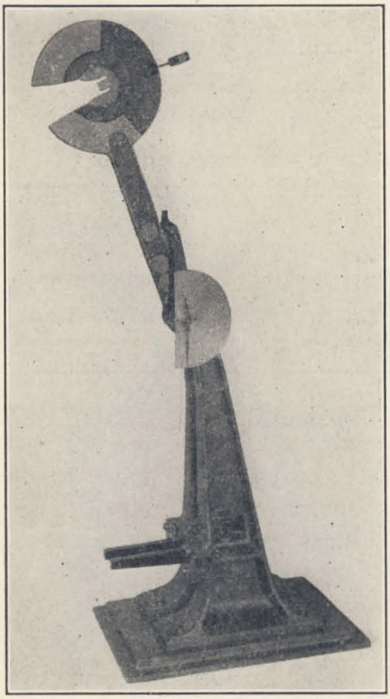


FIG. 50.—The Charpy Impact Machine.

Square and round, notched and unnotched, test bars are used in impact testing. The Charpy machine, Fig. 50, with a round tensile specimen, is commonly used in ordnance work. This machine comes within the first classification of impact-testing machines. Another common machine of this type is the Izod machine.

ALLOY STEELS AND ALLOY CAST IRON

The steels that have been described are called *carbon steels* to distinguish them from a large group of special steels known as *alloy steels.* Alloy steels have been defined as "those which owe their properties chiefly to the presence of an element (or elements) other than carbon."

121. Influence of Alloying Elements.—The metals or metalloids added to carbon steel in order to make an alloy steel operate to produce one or more of the following changes:

1. To modify the effect of heat treatment, by changing either the temperature of the critical ranges or the mode of occurrence of the critical changes. This effects, for example:

   a. Suppression of the critical range, thus giving austenitic steel at atmospheric temperatures.

   b. Change in the rate at which critical changes occur, thus giving extra hard martensitic steel or else sorbitic steel, etc.

   c. Lessening of the damage due to overheating, thus permitting quenching from near the melting point.

2. To form compounds or solid solutions with the carbon or with the iron.
3. To remove oxides or gases.
4. To change the form in which carbon occurs.

Almost all alloy steels are used in a heat-treated condition. They have this peculiarity in common: they retain a fair degree of toughness, as represented by the reduction of area, even when hardened so as to be very strong.

122. Classification of Alloying Elements.—Alloying elements used in steels may for convenience be classed under two groups:

1. The element is completely dissolved by the iron base or matrix.
2. The element is partly dissolved by the iron base or matrix and partly forms a "carbide."

Elements (group 1) which enter into solid solution with the iron usually enhance the strength and *toughness* of the steel. These *toughening* elements include nickel, silicon, cobalt, and copper. Elements (group 2) which are partially dissolved by the iron, and also form "carbides," have the general tendency to enhance both the toughness and *hardness* as well as to raise the tensile strength. This group includes manganese, molybdenum, vanadium, tungsten, and chromium.

No alloying element will satisfy all requirements; alone, it may be able to produce astonishing effects in steel, but other desired properties may be lacking in the product. For example, an alloy steel may be forgeable and machineable but fail in oxidation resistance; or, if oxidation resistant it may not be resistant to abrasion, or to shock. When an alloying element is used in proper combination with others, however, it may enhance their beneficial effects while, itself, contributing qualities which no other will provide so effectively.

123. Nickel Steels.—The presence of increasing proportions of nickel results in a continuous lowering of the critical temperatures. For nickel steels containing up to 5 per cent, each 1 per cent of nickel

lowers the critical range on heating about 10° C. below the corresponding range for carbon steels. Lower temperatures are therefore used in the heat treatments for nickel steels than are required for carbon steels with the same carbon content. On this account, less scaling, warping, and cracking of parts made of nickel steel occur during heat treating.

The group of nickel steels which is used most extensively contains from 3.25 per cent to 3.75 per cent of nickel. These alloy steels are available with the carbon ranging from 0.10 per cent to 0.55 per cent. The nickel steels with 0.10 per cent to 0.25 per cent carbon are used for machine parts which are to be case carburized. Other nickel steels containing 0.25 per cent to 0.55 per cent carbon are employed in the hardened and tempered condition for machine parts requiring high strength. Gears having large sections are often made of steel containing approximately 3.50 per cent of nickel and 0.50 per cent of carbon.

With proper heat treatment, nickel increases the strength and toughness of steel. It also intensifies the effects of other alloying elements, particularly chromium.

124. Chromium Steels.—Chromium occurs in steel as the double carbide of chromium and iron. Since chromium alone does not harden iron, it is necessary to have sufficient carbon present in steel to form the hard compounds. The outstanding effects of chromium are to increase the hardness and strength of steel after heat treatment, and to make the steel more resistant to corrosion. Increasing percentages of chromium in steel raise the critical temperature slightly above those for carbon steels, which accounts for the higher temperatures used in the heat treatments for chromium steels.

Chromium steels having a low carbon content are used for parts which are to be case carburized. The heat treatments for these steels are similar to those for plain carbon steels except that the quenching temperatures are about 30° C. higher than the temperatures used for corresponding carbon steels. The chromium steels with a medium carbon content possess greater strength and hardness after heat treating than can be obtained in plain carbon steels having the same carbon content. An alloy steel which is used chiefly for parts of ball and roller bearings contains 0.95 per cent to 1.10 per cent carbon and 1.20 per cent to 1.50 per cent chromium.

125. Corrosion-Resisting Steels.—Steels which contain more than 11 per cent of chromium possess favorable resistance to attack by various corroding influences and are employed extensively in equipment for dairies, bakeries, laundries, and chemical plants, as well as for

decorative purposes. There are at least three general types of these steels, differing in chemical composition and in physical properties.

One type of "stainless" steel which is used for applications requiring considerable hardness contains from 11 per cent to 14 per cent of chromium and about 0.35 per cent of carbon. In order to develop maximum resistance to corrosion, it is necessary to heat-treat this steel, and then to grind and polish it. This alloy steel is used in cutlery, and in surgical and dental instruments.

Large quantities of steel containing from 16 per cent to 20 per cent of chromium and less than 0.12 per cent of carbon are being produced for corrosion-resisting purposes. Heat treating is not necessary to develop its best corrosion resistance. This chromium steel is manufactured chiefly in the form of strips and sheets. It has a tensile strength of 75,000 lb. per sq. in. with an elongation of 25 per cent and a Brinell hardness of 175.

Another type of corrosion-resisting steel which is widely used contains approximately 18 per cent chromium and 8 per cent nickel with the carbon content usually less than 0.15 per cent. This steel is commonly known as "18–8" and is marketed under a number of trade names. An increase in hardness is brought about by cold-working the metal during forming and deep-drawing operations. In addition to its resistance to atmospheric corrosion, steel of this type does not scale appreciably when heated to 980° C. The tensile strength of 18–8 after heat-treating is about 85,000 lb. per sq. in., and the elongation 60 per cent; but the Brinell hardness is only about 130.

126. Nickel-chromium Steels.—Commercial specifications provide four groups of nickel-chromium steels having a carbon range from 0.10 per cent to 0.55 per cent. The nickel content of these steels is from $1\frac{1}{2}$ to 3 times the chromium content. Each of the alloying elements contributes its beneficial effects, and, as a result, steels having high strength and deep-hardening power are secured. Those steels with low carbon content are used for parts which are to be case carburized, and those with the higher carbon content are used for heat-treated forgings and shafting of large size.

127. Manganese Steels.—Steels containing from 1.25 per cent to 1.8 per cent manganese are used for oil well sucker rods, rifle barrels, and other applications where greater strength is required than can be obtained from carbon steel but where the extra cost of the higher alloy steels is not justified. They respond more readily to heat treatment than carbon steels and have a higher ratio of elastic limit to tensile strength. In order to avoid confusion with "manganese steel" these alloys are called *structural manganese steels.*

Increasing proportions of manganese in steel cause a lowering of the critical temperatures and a retarding effect on the transformation of austenite. When the manganese content is from 11 per cent to 14 per cent, together with a carbon content of 1.00 per cent to 1.40 per cent, a steel is produced with a structure composed largely of austenite, called *manganese steel.* One of the valuable properties of manganese steel is that its hardness is increased rapidly by cold-working. It is due to this characteristic that manganese steel is particularly advantageous for parts of equipment which are subjected to wear by a pounding or rolling action. Some typical examples of service of this kind are the plates for rock crushers; frogs, switches, and crossings for railroad tracks; dipper teeth and lips for excavating machinery; and gears, racks, and sheaves for many purposes.

128. Silico-manganese Steel.—An alloy steel containing approximately 0.50 per cent carbon, 2.00 per cent silicon, and 0.70 per cent manganese is used for leaf and coil springs.

129. Chrome-vanadium Steels.—Vanadium is often added to steel in combination with chromium. This combination of alloying elements produces steels having high strength as well as great resistance to wear and fatigue, although only about 0.18 per cent vanadium is required.

130. Molybdenum Steel.—Molybdenum tends to inhibit grain growth in steel and increases the range of temperature within which steel can be hardened. The critical temperature on heating for molybdenum steel is somewhat higher than that for the corresponding carbon steel. Molybdenum causes an increase in the tensile strength and hardness of steel without loss of ductility and without rapidly decreasing its machineability. Although some steels contain molybdenum as the only alloying element, molybdenum is often added to steel with chromium or with nickel. An important application of chromium-molybdenum steel is to be found in the tubing used in the construction of aircraft.

131. Alloy Tool Steels.—The important alloying elements in tool steels are tungsten, chromium, vanadium, manganese, and molybdenum. Tungsten and molybdenum increase the hardness of steel, inhibit grain growth, but make necessary the use of high tempering temperatures. Chromium has a pronounced hardening effect when present with sufficient carbon. Vanadium aids in obtaining a fine grain structure in tool steel. Manganese intensifies the hardness of steel when it is present in sufficient proportion together with other hardening elements. Many different combinations of these alloying elements are used in making steel for tools. Several types of alloy tool steel with their compositions, uses, and heat treatments will now be described.

132. High-speed Steel.—The alloy steel which is used most widely for cutting metals is known as *high-speed steel.* The composition of this steel includes approximately 0.65 per cent carbon, 18 per cent tungsten, 4 per cent chromium, and 1 per cent vanadium. The valuable characteristic of high-speed steel lies in its ability to maintain its hardness, strength, and cutting quality at high operating temperatures. This property of holding a cutting edge at the high temperatures caused by friction of the work on the tool is termed *red hardness.* A variety of tools including lathe and planer tools, drills, and milling cutters are made of high-speed steel.

Special Cutting Tools.—More recent developments in this field have included the use of cemented carbide tips for the cutting edges of tools. Small pieces of tungsten carbide and other extremely hard carbides are joined to the tough shank of the tool by brazing. The tool then consists of a very hard cutting edge backed up by a tough, shock-resistant shank. "Super"-high-speed steels have also been developed. Their composition is essentially that of the high-speed steel with the addition of appreciable quantities (5–18 per cent) of cobalt.

133. Wear-resisting Steel.—A type of steel, which is commonly designated as high-carbon, high-chromium tool steel, usually contains about 1.50 per cent carbon, 12.00 per cent chromium, and 1.00 per cent vanadium. The valuable characteristic of this steel is its great resistance to wear. It is used to advantage in shear blades, forming rolls, drawing dies, and mandrels.

134. Shock-resisting Steel.—A number of compositions of tool steel are being used for chisels and punches which are subjected to severe fatigue stresses. A superior grade of steel for this purpose contains about 0.50 per cent carbon, 2.00 per cent tungsten, 1.25 per cent chromium, and 0.25 per cent vanadium.

135. Non-deforming Steel.—Some tools such as punching dies, forming dies, threading dies, and gages, which cannot be ground all over after heat treating, are made of steel in which the minimum amount of change in size and shape takes place during the hardening and tempering operations. To meet this requirement, an alloy steel containing about 1.00 per cent carbon and 1.00 per cent to 1.25 per cent manganese is often used.

136. Alloy Cast Irons.—Cast iron differs from steel principally because the excess of carbon, above the 1.7 per cent that will dissolve in iron at 1150° C., is precipitated throughout the matrix as flakes of graphite, thereby causing most of the rest of the carbon also to precipitate. These particles of graphite form the path through which failure occurs and are the reason why cast iron is brittle. The matrix of cast

iron is usually much like steel of the same carbon content and it is possible, by carefully controlling the silicon content, the rate of cooling, etc., to cause any definite amount of the carbon to precipitate as graphite or to remain combined as Fe_3C in the matrix. The same alloying elements that are used in steel, and very similar heat treatments, have been found to improve the quality of the matrix and to control the size and distribution of the graphite particles. Ordinary gray cast iron has a tensile strength of about 25,000 lb. per sq. in. and very little ductility. Heat-treated alloy cast irons provide strengths up to 60,000 lb. per sq. in., with considerable improvement in ductility.

Nickel Cast Iron.—Nickel increases the strength and wear resistance of cast iron without increasing the hardness too much for good machineability. It is used in quantities from 0.50 per cent to 2.5 per cent for valve lifters, gears, bushings, valve bodies, etc.

Nickel-chromium Cast Iron.—Small amounts of chromium (usually less than 1 per cent) are often used with nickel to increase the hardness and strength. Pistons, automotive brake drums, cylinders, cams, etc., are made from nickel-chromium cast iron.

Molybdenum Cast Iron.—Molybdenum increases the toughness and ductility of cast iron. From 0.50 per cent to 1.00 per cent molybdenum is ordinarily used. In combination with nickel, it is used for the production of crankshafts that possess high strength and hardness, improved toughness, and marked resistance to fatigue.

CLASSIFICATION AND USES OF ALLOYS *

All metals and alloys can be separated into two groups: (*a*) the *ferrous*, or iron-base group; and (*b*) the non-ferrous group, including all but the iron-base alloys. In view of the wide variety of the alloys in each group further classification might be difficult were it not for the extensive work of standardization that has been carried out by the American Society for the Testing of Materials and the Society of Automotive Engineers. The classifications presented are used as standards throughout the United States. Non-standard alloys can be purchased but they are not carried in stock and are, consequently, much more expensive.

137. The Non-ferrous Alloys.—The non-ferrous metals and alloys have been divided into eight groups. Specification numbers assigned by the S.A.E. for each of these groups are listed in Table III. In many cases several grades of one material are available. In the following discussion, however, only the first grade will be considered.

* Data concerning standard classifications and uses of metals reprinted by permission from the Society of Automotive Engineers.

TABLE III

NON-FERROUS METALS CLASSIFICATION

Compositions	Spec. Numbers
Solders	1–9
White Bearing Metals	10–19, 100–199
Wrought Aluminum Alloys	20–29, 200–299
Cast Aluminum Alloys	30–39, 300–399
Cast Brass and Bronze	40–49, 60–69, 600–699
Wrought Copper and Copper Alloys	70–79, 700–799
Wires and Rods	80–89
Zinc Alloys (Die Casting)	90–99, 900–999

138. Solders.—Commercial solders are alloys of lead and tin. They are used for joining metals. Because of the low melting point of solder, joints made in this manner cannot be subjected to temperatures much above 180° C. Soldered joints are not as strong as those made by brazing or by welding. Standard solders have the composition shown in Table IV.

TABLE IV

PERCENTAGE COMPOSITION OF SOLDERS

Spec. No.	Sn	Pb (Approx.)	Sb (Max.)	Cu (Max.)	Zn + Al	Other Impurities (Max.)
1	49.5/50.5	50.0	0.12	0.08	None	0.10
2	44.55/45.45	55.0	0.12	0.08	None	0.10
3	39.60/40.40	60.0	0.12	0.08	None	0.10
4	24.50/25.50	75.0	0.12	0.08	None	0.10

Note.—The melting point is increased by raising the % Pb.

139. White Bearing Metals.—These alloys of tin, copper, lead, and antimony are known as *babbitt* metals. They are used where it is not economical or necessary to use antifriction ball or roller bearings.

TABLE V

COMPOSITION OF WHITE BEARING METALS

Spec. No.	Sn (Min.)	Cu	Sb	Pb (Max.)	Fe (Max.)	As (Max.)	Bi (Max.)	Zn + Al
10	90	4.0/5.0	4.0/5.0	0.35	0.08	0.10	0.08	None
11	86	5.0/6.5	6.0/7.5	0.35	0.08	0.10	0.08	None
12	59.5	2.25/3.75	9.5/11.5	26.0	0.08	....	0.08	None
13	4.5/5.5	0.50	9.25/10.75	86.0	....	0.20	....	None
14	9.25/10.75	0.50	14.0/16.0	76.0	....	0.20	....	None

TABLE VI

Composition, Strength, and Uses of Aluminum Casting Alloys

Spec. No.	Type	Percentage Composition *—(Remainder Aluminum)						Other Impurities (Max.)		Tensile Strength 1000 × lb./sq.in.	Elongation % in 2 in.	Uses
		Cu	Zn	Si	Fe	Mn	Mg	Ni				
30.....	1	7.0/8.5	0.20	(Zn+Si+Fe +Mn+Sn−max. 1.70)					None	18	1–3	General
31.....	1	2.25/3.25	12.5/14.5	(as for 30)	......	.....	....		None	25	1–3	Not used at elevated temp. or for resistance to corrosion.
31A....	1	2.0/3.5	9.0/11.5	....	1.25/1.75	.....	....		1.0	25	2.5	Same as 31.
32.....	1	11.0/13.5	0.20	(as for 30)	......	.....	....		None	19	min.	Manifolds; not good for shock.
320....	1	0.10	......	0.25	0.30	0.60	3.25/4.25		0.60	22	6	Carburetors; corrosion resistant.
33.....	1	6.0/8.0	2.5	2.0	1.5	.....	....		1.0	19	1.0–2.5	Crankcases, housings, cylinder heads.
35.....	1	0.40	0.2	4.5/6.0	0.8	0.3	0.05		0.3	17	3	Resists salt spray; manifolds; instruments.
36.....	1	7.0/8.5	0.2	1.0/1.5	0.8/1.4	0.3	trace		0.3	19	1–3	General.
37.....	Intermediate	0.3	0.2	12.0/13.0	0.8	0.5	trace		0.3	24	4	Requires special treatment. Resists salt spray.
322....	2 †	1.0/1.5	......	4.5/5.5	0.5	.....	0.4/0.6		0.3	27–36	4–0	Aircraft engines, cylinder heads.
321....	2	0.5/1.5	......	11.25/15.0	1.3	.....	0.7/1.3	1.0/3.0	0.3	....	....	Pistons—low coefficient of expansion.
323....	2	0.20	......	6.5/7.5	0.5	.....	0.2/0.4	....	0.3	26–30	5–3	High strength, corrosion resistant.
324....	2	0.20	......	0.20	0.30	.....	9.25/11.25	....	0.2	40	11	Trucks, railway cars, aircraft fittings.
34.....	2	9.25/10.75	0.20	(Fe + Si − 2.0)	1.50		0.15/0.35	....	0.6	26–34	....	Pistons, camshaft bearings, valve tappet guides.
38.....	2	4.0/5.0	0.20	1.2	1.2	0.3	0.05	....	0.2	29–36	6–0	Crankcases, automotive fittings.
39.....	2	3.75/4.25	......	0.7	1.0	.....	1.2/1.7	1.8/2.3	0.2	30–40	....	Pistons, cylinder heads.

* Compositions shown as one figure (i.e., 0.20) are *maximum* for the element.

† Properties given for type 2 alloys are as heat treated.

Note.—Aluminum die casting alloys not listed.

Babbitts 10 and 11 are expensive because of their high content of tin but they are the only ones suitable for heavy pressure and severe duty such as that encountered in connecting-rod and shaft bearings.

140. Cast Aluminum Alloys.—These alloys, like the wrought aluminum alloys, are of two types. Type 1 alloys are not subject to heat treatment. Type 2 alloys are improved markedly by heat treatment and are usually purchased in the heat-treated condition. These alloys should not be confused with the wrought alloys. The casting alloys, designed to be poured into molds, are not usually satisfactory for any type of forging operation. A summary of the aluminum casting alloys is given in Table VI.

141. Wrought-aluminum Alloys.—These alloys are of two types: type 1 in which the harder tempers are produced by cold-working to produce strain hardening, and type 2 in which the higher strengths are produced by heat-treatment processes. Type 1 alloys are designated as *soft*, for the annealed metal, and *hard*, for material that has been cold-worked the maximum amount that is commercially practicable. These alloys are summarized in Table VII.

TABLE VII

WROUGHT ALUMINUM ALLOYS

Spec. No.	Type	Percentage Composition					Tensile Strength 1000 × lb./sq. in.	Elongation % in 2 in.	Uses
		Al (min.)	Mg	Mn	Cu	Si			
20	1	96.0	0.9/1.4	0.9/1.4	0.20	....	29–38	18–1	
25	1	99.0	(commercially pure Al)			....	15–22	30–2	Panels for buses, cowling, airplanes; tubing, fuel lines.
29	1	97.0	....	1.0/1.5	0.20	....	19–27	25–1	Gasoline tanks, body panels.
24	2	92.0	1.25/1.75	0.3/0.9	3.6/4.7	....	35–65	18–8	Aircraft parts.
26	2	92.0	0.2/0.75	0.4/1.0	3.5/4.5	....	26–58	22–15	Duralumin; general aircraft use.
27	2	92.0	....	0.5/1.1	3.9/5.0	0.5/1.1	45–63	22–9	Connecting rods, crankcases, propellers.

142. Brass, Bronze, and Copper Alloys.—Brass is an alloy of copper and zinc.

Bronze is an alloy of copper and tin deoxidized with phosphorus, silicon, or other deoxidizers. Alloys having a bronze color, other than those essentially copper and tin, are designated by a prefix, viz., commercial bronze and hardware bronze, alloys of copper and zinc with a bronze color. The latter contains a small amount of lead to give it good machining properties. There are also manganese bronze, Tobin bronze, and extruded architectural bronze which are alloys of copper and zinc having additions of tin, manganese, iron, nickel, or other metals. Aluminum bronzes are alloys of copper and aluminum. Sometimes they carry small percentages of iron, tin, nickel, or other metals. Cast bronzes are usually alloys of copper and tin with varying amounts of zinc or lead, or both, to give them desirable properties.

Bearings or gears made of bronze alloys should be used only against hardened steel. Both the wrought and the cast alloys will be considered in this section. The classification of Table VIII gives the general characteristics and general uses of the more important copper alloys.

143. Magnesium Alloys.—Magnesium is the lightest of the structural metals and, as with aluminum, its industrial uses can be attributed primarily to this property. Magnesium is used as a structural material only in the alloyed form; never as the pure metal. The principal elements used for the production of commercial magnesium alloys are aluminum, manganese, zinc, tin, cadmium, and copper. The alloys containing 8 per cent to 12 per cent Al are susceptible to heat treatment with resultant properties almost equal to those of the aluminum alloys. It is possible to obtain tensile strengths of 30,000 to 40,000 lb. per sq. in., with elongation from 15 per cent to 5 per cent. The magnesium alloys are used in the aircraft and automotive industries and for general structural work when it is essential to obtain strong materials even lighter in weight than the aluminum alloys.

144. Ferrous Alloys.—A numeral index system is used to identify the compositions of the S. A. E. steels, which makes it possible to use numerals on shop drawings and blueprints that are partially descriptive of the composition of material covered by such numbers. The War Department has adopted this system, using the letters W. D., instead of S. A. E., before the steel number. The first digit indicates the type to which the steel belongs; thus "1—" indicates a carbon steel; "2—" a nickel steel; and "3—" a nickel-chromium steel. In the simple alloy steels the second digit generally indicates the approximate percentage of the predominant alloying element. Usually the last two or three digits indicate the average carbon content in "points," or hundredths of 1 per cent. Thus "2340" indicates a nickel steel of approximately 3 per cent nickel (3.25 to 3.75) and 0.40 per cent carbon (0.35 to 0.45); and "71360"

TABLE VIII

CLASSIFICATION OF COPPER BASE ALLOYS

Alloys	General Composition, Per Cent				General Characteristics	General Uses
	Copper	Zinc	Lead	Tin		
Commercial Bronze 95 Per Cent	95.0	5.0	....	....	Copper colored, pliable.	Primer cups, bullet jackets, jewelry.
Commercial Bronze 90 Per Cent	90.0	10.0	....	....	Resists corrosion and atmospheric action.	Automobile radiators, screens, radios.
Red Brass 85 Per Cent	85.0	15.0	....	....	Resists corrosion and atmospheric action.	Tubing, hardware.
Red Brass 80 Per Cent	80.0	20.0	....	....	Resists sea water and atmospheric corrosion.	
Brazing Brass	75.0	25.0	....	....		Parts to be brazed or silver soldered.
Spring Brass	72.0	28.0	....	....	Withstands drastic treatment.	Springs, rods, etc.
Cartridge Brass Grade A Comm.	70.0	30.0	....	....		Seamless tubes, deep drawings, cartridge cases.
Eyelet Brass Grade B Comm.	68.0	32.0	....	....		Eyelets, drawn shells.
Drawing or Spinning Brass	66.67	33.33	....	....		Deep drawings.
Commercial Brass Grade C	65.0	35.0	....	....	Not good for weather exposure unless annealed.	Fixtures, radiators, ornaments.
Brass Wire	63.0	37.0	....	....		Rivets, pins, screws, heading operations.
Muntz Metal	60.0	40.0	....	....	Worked hot, finished by slightly cold-working.	Bolts, nuts, sheathing, wire.
Leaded Low Brass	78.5	20.0	1.5	....	Free cutting.	Rivets, similar articles.
Turning Rod	62.0	35.0	3.0	....	Machines easily.	Automatic machine work.
Clock Brass	61.5	37.0	1.5	....	Free milling.	Meter and clock parts, gears.
Admiralty Metal	70.0	29.0	....	1.0	Resistant to sea water.	Condenser tubes, ferrules.
Tobin Bronze or Naval Brass	60.0	39.25	....	0.75	Stronger than commercial brass rod. Resistant to sea water.	Rods, bolts, nuts, piston rods, propeller shafts, plates.
Everdur, Cast	94.4	Si 4.5	Mn 1.0	....	Has corrosion-resisting properties of copper and physical properties of mild steel.	Cold- or hot-rolled, forged.
Everdur, Wrought	96.0	3.0	1.0	....		
Monel Metal	Copper 23		Nickel 67		High strength and toughness and excellent corrosion resistance.	Substitute for steel where service required justifies extra expense.

indicates a tungsten steel of about 13 per cent tungsten (12 to 15) and 0.60 per cent carbon (0.50 to 0.70).

In some instances, in order to avoid confusion, it has been found necessary to depart from this system of identifying the approximate alloy composition of a steel by varying the second and third digits of the number. An instance of such departure is found in the steel numbers selected for several of the corrosion- and heat-resisting alloys.

The basic numerals for the various types of S. A. E. steel are:

TYPE OF STEEL	NUMERALS (AND DIGITS)
Carbon Steels	1xxx
Plain Carbon	10xx
Free Cutting (Screw Stock)	11xx
Free Cutting, Manganese	X13xx
High Manganese	T13xx
Nickel Steels	2xxx
0.50 Per Cent Nickel	20xx
1.50 Per Cent Nickel	21xx
3.50 Per Cent Nickel	23xx
5.00 Per Cent Nickel	25xx
Nickel Chromium Steels	3xxx
1.25 Per Cent Nickel, 0.60 Per Cent Chromium	31xx
1.75 Per Cent Nickel, 1.00 Per Cent Chromium	32xx
3.50 Per Cent Nickel, 1.50 Per Cent Chromium	33xx
3.00 Per Cent Nickel, 0.80 Per Cent Chromium	34xx
Corrosion and Heat-resisting Steels	30xxx
Molybdenum Steels	4xxx
Chromium	41xx
Chromium Nickel	43xx
Nickel	46xx and 48xx
Chromium Steels	5xxx
Low Chromium	51xx
Medium Chromium	52xxx
Corrosion and Heat Resisting	51xxx
Chromium Vanadium Steels	6xxx
Tungsten Steels	7xxx and 7xxxx
Silicon Manganese Steels	9xxx

The prefix "X" is used in several instances to denote variations in the range of manganese, sulphur or chromium.

The prefix "T" is used with the manganese steels (1300 Series) to avoid confusion with steels of somewhat different manganese range that have been identified by the same numerals but without the prefix.

A few typical chemical analyses are given in Table IX to illustrate the operation of this system.

TABLE IX

Chemical Composition—SAE Steels

SAE or (WD) No.	Carbon	Manganese	Phosphorus (Max.)	Sulphur (Max.)	Nickel	Chromium
1040	0.35–0.45	0.60–0.90	0.045	0.055	....	....
2350	0.45–0.55	0.60–0.90	0.040	0.050	3.25–3.75	....
3130	0.25–0.35	0.50–0.80	0.040	0.050	1.00–1.50	0.45–0.75
52100	0.95–1.10	0.20–0.50	0.030	0.035	....	1.20–1.50
30915	0.09–0.20	0.20–0.70	0.030	0.030	8.0 –10.0	17.0 –20.0

General uses of some of the alloy steels were given under the discussion of those steels. The plain carbon steels may be classified as to use as shown in Table X.

TABLE X

Carbon Content of Steels for Different Uses

Carbon Range, Per Cent	Uses of Carbon Steel
0.05–0.15	Pipe, chain, rivets, screws, nails.
0.15–0.25	Structural shapes, plates, bars.
0.25–0.35	Machine parts requiring medium strength.
0.35–0.55	Machine parts requiring high strength.
0.60–0.70	Dies for drop hammers, set screws, locomotive tires.
0.70–0.80	Anvil faces, band saws, smithing hammers, pickaxes.
0.80–0.90	Punches, rock drills, cold chisels, rivet sets.
0.90–1.00	Springs, axes, knives, shear blades.
1.00–1.10	Milling cutters, flat drills, taps.
1.10–1.20	Lathe tools, twist drills, wood chisels.
1.20–1.30	Files, reamers.
1.30–1.40	Wire-drawing dies, razors, brass-turning tools.
1.40–1.50	Saws for cutting steel.

ORDNANCE USES

145. In the construction of ordnance matériel use is made of all the foregoing ferrous and non-ferrous alloys and of numerous special alloys developed specifically for ordnance use. Substitution of newer alloys for older ones is constantly being made. It is, therefore, impossible to give an up-to-date list of the metals used in the various items of ordnance equipment. However, Table XI gives a partial list of the materials that have proved satisfactory.

TABLE XI

METALS AND ALLOYS USED IN ORDNANCE

Use	Material	Specification No.
1. Gun Barrels		
(*a*) Rifle	Steel	1350; 4150
(*b*) Machine gun	Steel	5050; 5150
(*c*) Artillery (forgings)	Steel	2340; 4640
2. Gun Carriages		
(*a*) Bolted and riveted castings	Steel	Steel castings 1035
(*b*) Built-up welded	Steel	2330
(*c*) Traversing and elevating gears	Manganese Bronze	43
3. Recoil Mechanisms	Stainless Steel, Monel Metal	51335; 30915; Monel
4. Automotive Parts		
(*a*) Steering knuckles	Steel	2335; 3130; 3135; 3140
(*b*) King pins	Steel	2315; 2520; 3115; 4615
(*c*) Transmission gears	Steel	2320; 2512; 3250; 4640
(*d*) Universal joints	Steel	2315; 4615
(*e*) Connecting rods	Steel	3135
(*f*) Piston pins	Steel	2315; 2512; 4615
(*g*) Roller bearings	Steel	4620; 4340; 52100
5. Instruments—Fire control, etc	Aluminum Alloys	26; 35; 30
6. Ammunition		
(*a*) A. P. projectiles	Steel	3250
(*b*) H. E. shell, shrapnel cases	Steel	1065
(*c*) Cartridge cases	Brass	(Cu 70; Zn 30)
(*d*) Bullet jackets, rotating bands	Gilding metal	(Cu 90; Zn 10)
(*e*) Target-practice projectiles	Cast iron	111

Note.—All steels in this table ending in digits 12, 15, and 20, are case hardened before use, except 30915.

CHAPTER V

GUNS

BASIC CONSIDERATIONS

146. Theory of Elasticity.—In mechanics, as ordinarily treated, solid bodies are considered "rigid," that is, they are supposed to retain all their dimensions unaltered under the action of the various forces to which they may be subjected. Whereas this assumption is frequently true if only the final condition of the bodies (after the action of the forces has ceased) is considered, it is found that all bodies are more or less deformed during the time the forces are acting. The theory of elasticity deals with the nature and amount of this deformation in various parts of the bodies under consideration and with the forces transmitted by those parts. Before examining this deformation more closely, it is necessary to define and to explain some of the terms most generally used in a discussion of this subject, whether the material be a metal, wood, or other substance.

147. Relation between Stress and Strain.—When an external force is applied to a rigid body in one direction only, as in a test specimen subjected to a load in tension or to compression in a testing machine, a corresponding tensile or compressive stress is developed in that direction by the applied load. This unit stress, obtained by dividing the load by the area on which the force is applied, will be referred to as the applied or *simple* stress in the direction under consideration. If the simple stress *does not exceed the proportional limit* the strain produced in the same direction will be equal to the simple stress divided by the modulus of elasticity. This constant relation between stress and strain, known as *Hooke's law*, may be expressed:

$$E = \frac{s}{e} = \frac{\dfrac{F}{A}}{\dfrac{L_2 - L_1}{L_1}}$$

where E = modulus of elasticity in pounds per square inch.

s = simple stress per unit area in pounds per square inch.

e = strain per unit of length in inches per inch.
F = total applied load in pounds.
A = original cross-sectional area in square inches.
L_2 = length under load in inches.
L_1 = original length in inches.

The relationship expressed by Hooke's law is applicable to an applied load and the corresponding strain in one direction only. In practice the applied loads are much more complex and a particular part of the structure may be subjected to simultaneous tensile, compressive, and shearing loads, each applied in a different direction. As will be shown later, each load modifies the strain produced by every other load and there may be simple stresses in particular directions in excess of the elastic limit, while the resultant strains in these directions remain less than the strain corresponding to the elastic limit; or the conditions may be such that the simple stress is below the elastic limit and the resultant strain in the same direction is in excess of that corresponding to the elastic limit.

148. Strains Perpendicular to Direction of Simple Stress.—When a material is subjected to a single tensile or compressive stress, there is not only a strain in the direction of that stress, but also a strain in all directions perpendicular to that direction. If the cube in Fig. 51 is subjected to the simple tensile stress represented by s, the edges aa, bb, etc., parallel to the direction of this stress will be elongated and the edges ab, ac, etc., perpendicular to this direction will be shortened. The amount of this shortening will be less than the elongation of the edges aa, etc. The strains in perpendicular directions will always be opposite in character to that in the direction of the stress.

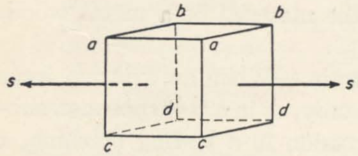


FIG. 51

The ratio of the unit strain in the perpendicular directions to that in directions parallel to the simple stress is known as *Poisson's ratio*, and varies for different materials, depending upon the elementary crystal structure of the material. It is about 0.25 for glass and about 0.43 for lead. The elementary structure of gun steel is the cube and the value of $\frac{1}{3}$ for Poisson's ratio is generally accepted for this material. The volume, and consequently the density, of a body under stress is usually changed slightly from its value before the stress was applied.

It is apparent that when loads are applied in two or more directions, each load modifies the strain produced by every other load, and that the total strain at any point in any one direction will be different from

the strain produced by the simple stress, if any, in that direction. The hypothetical stress, which acting alone would produce this total or combined strain, is calculated by multiplying the strain by the modulus of elasticity and will be referred to as the *resultant stress* at the given point in the given direction. When the directions being considered are the three customary rectangular coordinate axes through the given point, the resultant stresses in those directions are the principal stresses.

If we consider the cube of Fig. 52 to be 1 in. on a side and to be subjected to simple tensile stresses applied simultaneously in the three directions perpendicular to its faces, the strain in each direction due

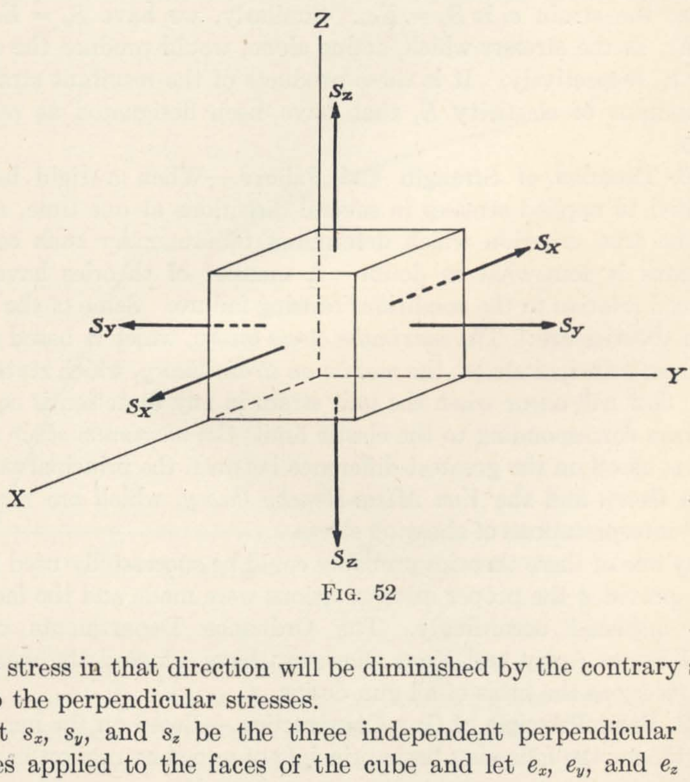


FIG. 52

to the stress in that direction will be diminished by the contrary strains due to the perpendicular stresses.

Let s_x, s_y, and s_z be the three independent perpendicular tensile stresses applied to the faces of the cube and let e_x, e_y, and e_z be the resultant strains in the directions of X, Y, and Z, respectively. The tensile strain in the direction of X that would be produced by s_x acting alone is s_x/E (E being the modulus of elasticity for gun steels, taken as 30,000,000 in practical work). This is diminished by the compressive strains in this direction produced by s_y and s_z. These are $s_y/3E$ and $s_z/3E$, respectively. Similar relations hold in the direction of Y and Z. We have, therefore, for the resultant strains in three directions,

$$\left.\begin{aligned}
&(a)\quad e_x = \frac{1}{E}\left[s_x - \frac{s_y}{3} - \frac{s_z}{3}\right]\\
&(b)\quad e_y = \frac{1}{E}\left[s_y - \frac{s_z}{3} - \frac{s_x}{3}\right]\\
&(c)\quad e_z = \frac{1}{E}\left[s_z - \frac{s_x}{3} - \frac{s_y}{3}\right]
\end{aligned}\right\} \qquad (1)$$

The tensile stress which, acting alone in the direction of X, would produce the strain e_x is $S_x = Ee_x$. Similarly, we have $S_y = Ee_y$ and $S_z = Ee_z$ as the stresses which, acting alone, would produce the strains e_y and e_z, respectively. It is these products of the resultant strains by the modulus of elasticity E, that have been designated as *resultant stresses.*

149. Theories of Strength and Failure.—When a rigid body is subjected to applied stresses in several directions at one time, as in a gun, the true criterion which determines failure under such complex conditions is somewhat in doubt. A number of theories have been advanced relative to the conditions causing failure. Some of the better known theories are:* The *maximum stress theory,* which is based on the maximum principal stress; the *maximum strain theory,* which states that plastic flow will occur when the unit strain in any direction is equal to the strain corresponding to the elastic limit; the *maximum shear theory,* which is based on the greatest difference between the principal stresses; *Mohr's theory* and the *Von Mises-Hencky theory,* which are based on special interpretations of shearing stresses.

Any one of these theories probably could be successfully used in gun design provided the proper interpretations were made and the factor of safety adjusted accordingly. The Ordnance Departments of the United States Army and Navy, however, have adopted the *maximum strain theory* as the basis of all gun design.

150. Basic Principle of Gun Construction.—Based on the maximum strain theory the following basic principle of gun construction has been adopted:

No part of the gun should be strained beyond the strain corresponding to the elastic limit of the metal as determined by the usual tension and compression tests.

We have seen how it is possible by the use of Poisson's ratio and the

* For a more complete discussion of these theories see A. Nadai, "Plasticity," pp. 59 ff.

modulus of elasticity to consider a combination of stresses acting at right angles, and to determine for each principal direction a hypothetical or *resultant stress* which if acting alone would produce the actual existing strain in that direction. With this in mind we can restate the basic principle of gun construction as follows:

No part of the gun should be subjected to a resultant stress beyond the elastic limit of the metal as determined by the usual tension and compression tests.

151. Effect of Overstrain of Metal.—We have seen that there is a definite proportionality between stress and strain as long as the metal is not stressed beyond the elastic limit. When the elastic limit is ex-

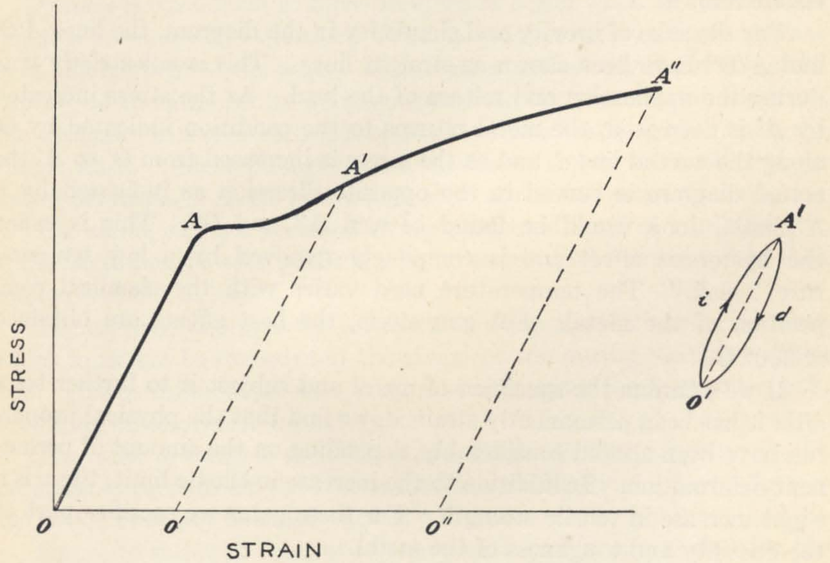


FIG. 53.

ceeded, however, the proportionality no longer holds true, for the metal becomes partially plastic showing an increased but varying ratio of strain to stress. The nature and the amount of this change vary with different metals and with the different alloys of steel. For a typical gun steel the stress-strain diagram is shown in Fig. 53. If the elastic limit, A, is not exceeded, the metal will of course return to its original dimension by the line AO as the stress is released. If the stress is carried to some point in excess of the elastic limit, as A', the releasing of the stress will not cause the return of the metal to its original dimension along the line AO. It will, however, return approximately along the parallel line $A'O'$ to the point O'. When all the applied stress has been released

there will be a permanent strain or "set" remaining in the metal, as indicated by the distance OO'. If the stress be again applied as before, the diagram will now follow very close to the line $O'A'$, and, if released at any point on this line, it will return by the same line to O'. This indicates that the metal now has a new elastic limit A'.

If we again subject the metal to a stress and continue beyond the point A', we find that the curve will follow the line $A'A''$. If we release the stress at any point along this line, say A'', we find that the metal behaves in a similar manner, that is, the curve will again be parallel to the line AO but this time the path is indicated by the line $A''O''$. And for subsequent applications of the load we find that there is now a new elastic limit at A''.

For the sake of brevity and simplicity in the diagram, the lines $A'O'$ and $A''O''$ have been shown as straight lines. This is not strictly true during the application and release of the load. As the stress indicated by A' is decreased, the metal returns to the condition indicated by O' along the curved line d, and as the stress is increased from O' to A' the actual diagram is curved in the opposite direction as indicated by i. A similar loop would be found betwen A'' and O''. This is called the hysteresis effect and is completely removed by a low temperature "soak." The temperature used varies with the chemical composition of the metal. For gun steels, the best effects are obtained at 300° C.

If we examine the specimen of metal and subject it to further tests after it has been permanently strained, we find that the physical properties have been altered considerably, depending on the amount of permanent deformation. In addition to the increase in elastic limit, there is a slight increase in tensile strength. For these gains we sacrifice part of the ductility and toughness of the metal.

It is obvious that the overstrain or "cold working" of the metal of a *completed* gun could have no practical application, for the basic principle of gun construction states that no part of the gun should be strained beyond the strain corresponding to the elastic limit. We shall see later that the practical application lies in deliberately stressing an unfinished gun beyond its elastic limit before it is machined to final dimensions. After the gun is completed, the new elastic limit must never be exceeded.

CONSTRUCTION OF GUNS

152. Definitions.—A gun or a cannon may be considered as a tube or hollow cylinder designed to withstand a given pressure from within, and capable of discharging a projectile with a high velocity. The

classification of guns into their several types, such as mortars, howitzers, etc., will be considered in a later chapter.

Wall ratio is the ratio of the outside radius to the inside radius, or of the corresponding diameters.

The *bore* of a gun is the inside surface of the tube. It is usually of uniform diameter from the powder chamber to the muzzle.

The *caliber* of a gun is the diameter of its bore. The term *caliber* is also used as a unit in expressing its length. For example, a 12-in., 50-caliber gun is a gun whose bore is 12 in. in diameter and whose length, measured from breech face to muzzle, is 50 calibers, that is, 50 units of 12 in. or 50 ft.

Failure is considered to have occurred in a gun when any part of the metal is permanently deformed. This is usually evidenced by a permanent enlargement of the bore. Failure does not usually mean an actual rupture of the gun, for as we have seen from the stress-strain diagram, the ultimate or tensile strength of steel is considerably higher than the elastic limit. When failure occurs, however, a gun is considered no longer serviceable, as its power and accuracy have been impaired.

The *elastic strength pressure*, or the computed limit of gun strength, is the maximum powder pressure which the gun could withstand at that section without failure.

The *permissible pressure* at any section of a gun is the powder pressure which must not be exceeded at the given section during the firing of the gun. This permissible pressure is considerably under the elastic strength, providing an allowance for safety.

The *factor of safety* is the ratio of the elastic strength pressure to the permissible pressure at the section under consideration. In our service the factor of safety is usually about 1.5

Figure 54 shows the outline of a gun, with typical curves showing the variation in elastic strength pressure (A), permissible pressure (B), and powder pressure (C), along the length of a gun. The abscissa is "distance traveled by projectile" and the ordinate is interior pressure.

The factor of safety at any section would be the ratio of the ordinate of curve A at that section to the corresponding ordinate of curve B. As the projectile travels down the bore, the powder pressure rises from zero to a maximum. It will be noticed however, that the strength pressure curve starts at its maximum value and that it does not commence to decrease until after the powder pressure curve has passed its maximum. This is due to the fact that when the base of the projectile is at the position corresponding to the maximum powder pressure, the powder chamber and all parts of the bore to the left of this point are subjected to this pressure. To the right of this maximum, the strength

pressure curve decreases to its minimum value near the muzzle. This permits a much lighter weapon than would a perfectly cylindrical shape, without sacrificing any element of safety. Practical considerations, however, limit the extent to which the strength pressure curve may follow the shape of the powder pressure curve.

153. Early Methods of Construction.—Up to the time of the Civil War all cannon were cast in one piece, the material used being either bronze or cast iron. When stronger guns were needed, the additional strength was obtained by sheer weight of metal. As the size of pro-

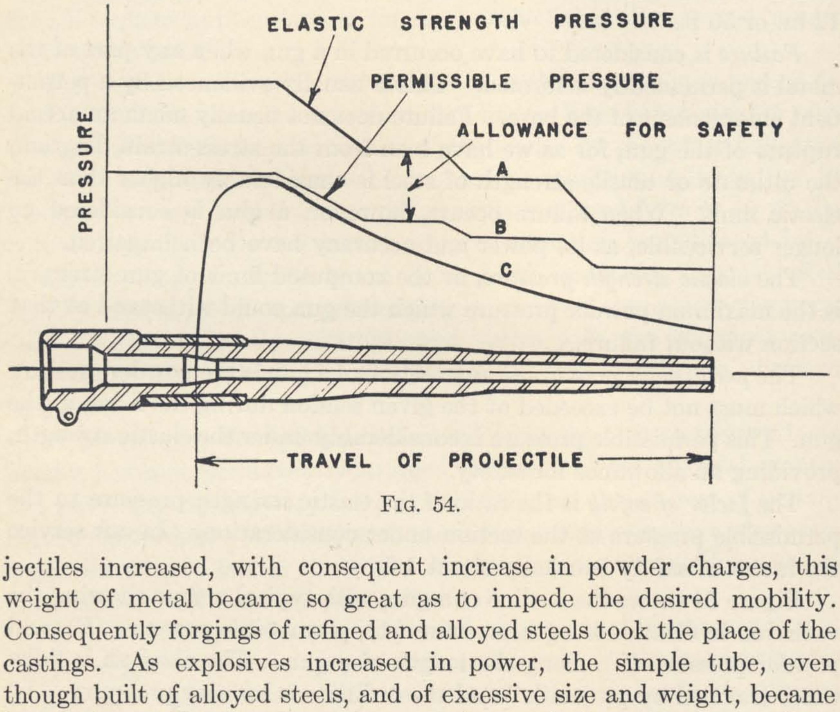


FIG. 54.

jectiles increased, with consequent increase in powder charges, this weight of metal became so great as to impede the desired mobility. Consequently forgings of refined and alloyed steels took the place of the castings. As explosives increased in power, the simple tube, even though built of alloyed steels, and of excessive size and weight, became incapable of retaining the pressures. As we shall see later, very little strength can be gained by increasing the wall ratio beyond a limited amount.

154. Present Methods of Gun Construction.—The problem of sufficient strength without excessive weight has been met by the construction of built-up, wire-wrapped, and cold-worked guns. Guns constructed by each of these methods are to be found in our service today.

Failure, if it occurs in a one-piece or monobloc gun, is due to the metal near the bore becoming overstressed in tension in a tangential

direction. The powder pressure is limited to that which will not stress this metal beyond its elastic limit in tension. By constructing a gun in such a manner that the metal near the bore is under *compression* when the gun is at rest, we can greatly increase the allowable powder pressure, for part of the powder pressure acts merely to relieve this initial compression. And when the compression is all relieved, the gun will still stand such additional pressure as to take the metal to its elastic limit in tension. This principle is utilized in all three of the present standard methods of construction.

Built-up Guns.—A built-up gun consists of two or more concentric cylinders, assembled by shrinkage methods. For example, the two-piece gun is assembled by shrinking the outer cylinder (jacket) onto the inner cylinder (tube). The inside diameter of the jacket is made slightly smaller than the outside diameter of the tube. The jacket is expanded by heat until it fits over the tube. Then, as it is cooled, the jacket shrinks into place, the process putting the tube into a state of compression, and increasing the elastic strength of the gun as previously explained.

Some guns have a breech ring which is screwed on the rear of the jacket and forms the breech recess, in which case the jacket extends only to the breech ring. Built-up guns of larger caliber have one or more layers of hoops at the breech end in addition to the jacket, one layer of hoops extending to the muzzle.

The bore of the tube forms the powder chamber, the seat for the projectile, and the rifled bore. Except on guns provided with a breech ring, the jacket extends to the rear of the tube a sufficient distance to allow the seat for the breechblock to be formed in the bore of the jacket. Through the bearing of the breechblock in the jacket or breech ring, the longitudinal stress due to the pressure of the powder gases is transmitted to the jacket either directly or indirectly through the breech ring. The metal of the tube is thus relieved from this stress.

The construction of an early model of the 3-in. antiaircraft gun is shown at the top of Fig. 55. This also represents the common practice for field-gun construction. There is a shoulder on the tube just forward of the jacket. This shoulder and the forward end of the jacket are threaded with a broad screw thread. The rear end of the locking hoop or ring is provided with a similar female thread. The locking hoop or ring is both screwed and shrunk on the tube and jacket, holding the two firmly together. In some cases the shoulder on the tube is not threaded, but the locking ring, which is screwed to the jacket and also shrunk on both tube and jacket, holds the two together by means of a bearing against the shoulder on the tube.

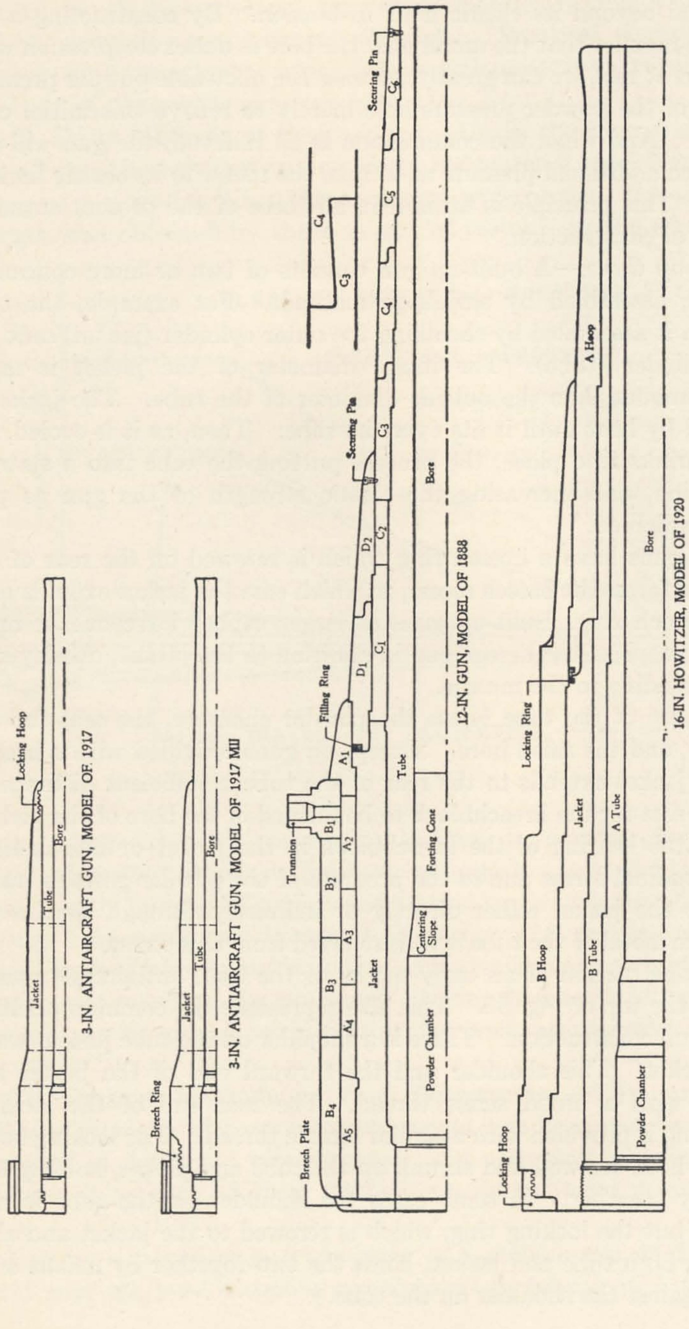

Locking Hoop
Breech Ring
Jacket
Tube
Bore
3-IN. ANTIAIRCRAFT GUN, MODEL OF 1917
Breech Ring
Jacket
Tube
Bore
3-IN. ANTIAIRCRAFT GUN, MODEL OF 1917 MII
Breech Plate
Trunnion
Filling Ring
Securing Pin
Securing Pin
B_4
A_5
A_4
B_3
A_3
B_2
A_2
B_1
A_1
D_1
C_1
D_2
C_2
C_3
C_4
C_5
C_6
C_3
C_4
Jacket
Tube
Powder Chamber
Centering Slope
Forcing Cone
Bore
12-IN. GUN, MODEL OF 1888
Locking Hoop
Locking Ring
B Hoop
Jacket
A Hoop
B Tube
A Tube
Powder Chamber
Bore
16-IN. HOWITZER, MODEL OF 1920

FIG. 55.

In the second antiaircraft gun shown in Fig. 55, the seat for the breechblock is formed in the breech ring instead of in the rear of the jacket. The breech ring is screwed on the rear end of the jacket with a slight shrinkage and is locked in place by a lock screw. This method of construction greatly simplifies the fabrication of the jacket. The rear of the tube bears against a shoulder on the breech ring. The tube is prevented from moving forward by means of a shoulder on the jacket which bears against a corresponding shoulder on the tube.

The 12-in. Gun, Model of 1888, shown in Fig. 55, illustrates one of the earliest models of large caliber, built-up guns manufactured in America. At the bottom of this figure is shown the 16-in. Howitzer, Model of 1920, which is a modern type of large built-up cannon. In the newer models, the number of hoops has been greatly decreased. This reduction has been made possible by the progress in the manufacture of larger pieces of forged steel and increases the longitudinal strength and stiffness of the gun. Instead of a single tube, the larger guns of more recent design may contain a second tube or liner, as shown in the figure. In the howitzer shown, the jacket, A-hoop, B-hoop, and locking rings are first assembled over the B-tube by shrinkage. This entire assembly is then shrunk over the A-tube or liner. The liner is put in last to facilitate removal. This part of the cannon contains the rifling and may be replaced after the rifling has become badly worn without affecting the serviceability of the rest of the cannon. This work cannot be done in the field, so the cannon must be removed from its carriage and sent to an arsenal for this class of repair.

In all built-up guns there is some method of locking the tube to the jacket to prevent relative movement of these parts while under pressure of the powder gases.

The hoops also are locked together by the various methods shown in Fig. 55. The joint between the C3-hoop and the C4-hoop in the 12-in. gun is coned, as indicated in the exaggerated sketch, the base of the cone being toward the muzzle. The D1-, D2-, C4-, C5-, and C6-hoops are locked together by similar joints. On the older guns with a large number of hoops, securing pins were used to assist in preventing forward movement of the hoops under the vibration set up by the shock of discharge.

As the metal at the muzzle receives support from one side only, the thickness of metal at this section is increased in some guns to make the wall strength equal to that of the nearby sections.

Wire-wrapped Guns.—Wire-wrapped guns are assembled by wrapping wire under tension on a central tube. The wire puts the metal of the tube under compression, giving the same effect as in the built-up guns

assembled by shrinkage. An outer cylinder or jacket is generally shrunk on over the wire.

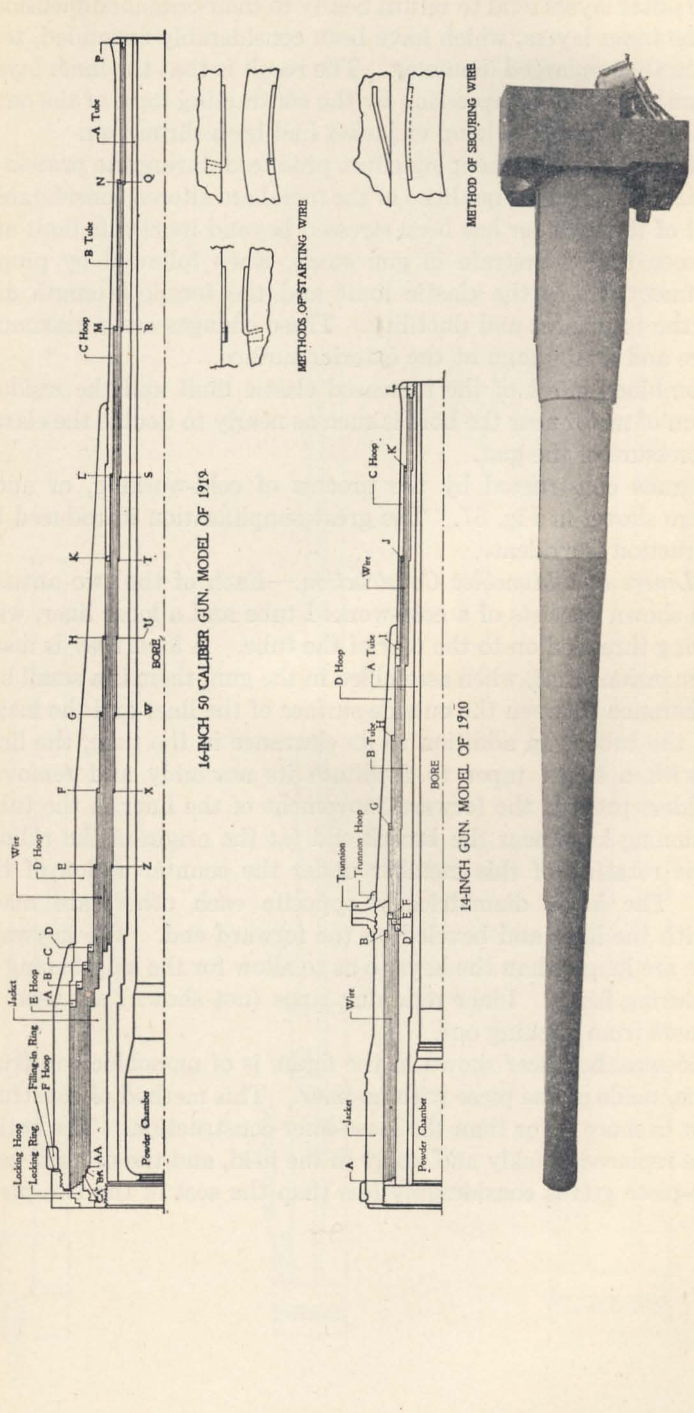
Figure 56 shows the 16-in., 50 caliber Gun, Model of 1919, which is of the wire-wrapped type and is representative of recent practice in the construction of guns by this method. This gun also contains two tubes. As in the case of built-up guns, the inner or A-tube is provided to facilitate relining when the rifling has become badly worn. In assembling, the jacket is shrunk over the rear of the B-tube. Over the length of this unit of tube and jacket, from the locking ring at the breech to the P-ring at the muzzle, is wound an envelope of wire. The wire is of square cross section, approximately 0.1 in. on a side.

On the older type of wire-wrapped guns, the jacket was shrunk over the wire envelope at the rear of the guns, hoops being used to cover only that portion of the wire envelope in front of the jacket. The 14-in. Gun, Model of 1910, shown also in Fig. 56, is an example of this type of construction.

At the present time there are no cannon being made in this country by wire wrapping. The advance that has been made during recent years in the quality of large forgings and in methods of inspection now makes it possible to get suitable forgings for jackets and hoops of all sizes. Built-up guns, assembled by shrinkage, can now be produced faster and with equally satisfactory results. Wire-wrapped guns do not have the rigidity of other built-up guns, this becoming evident in the larger calibers by an increased "droop" and a tendency towards greater "whip" action under the firing stresses. The process of relining wire-wrapped guns when they are worn is much more difficult and in some cases unsatisfactory.

Cold-worked Guns.—In a built-up gun we have seen how the tube is put under a state of compression because of the exterior pressure exerted by the jacket and the hoops. Shortly before the World War, the *cold-working* or *radial-expansion* process of gun making was devised to produce this compression without hoops. The method as originally developed was termed *auto-frettage,* which literally translated from the French, means "self-hooping." Cannon of all sizes up to the 155-mm. gun have been successfully manufactured by this process; and it is standard for all new designs up to 8 in. in caliber.

The process consists essentially of taking a single cylinder, with the interior diameter slightly less than the caliber desired, and subjecting it to an interior hydraulic pressure of sufficient intensity to enlarge the bore permanently about 6 per cent. The outside diameter of the cylinder is enlarged only very slightly, running only about 1 per cent for the average wall ratio used. When the hydraulic pressure is re-



16-INCH 50 CALIBER GUN, MODEL OF 1919.

FIG. 56.

leased, the outer layers tend to return nearly to their original dimensions, whereas the inner layers, which have been considerably expanded, tend to maintain their enlarged diameter. The result is that the inner layers of metal are put under compression by the contracting force of the outer layers exactly as though a hoop or jacket had been shrunk on.

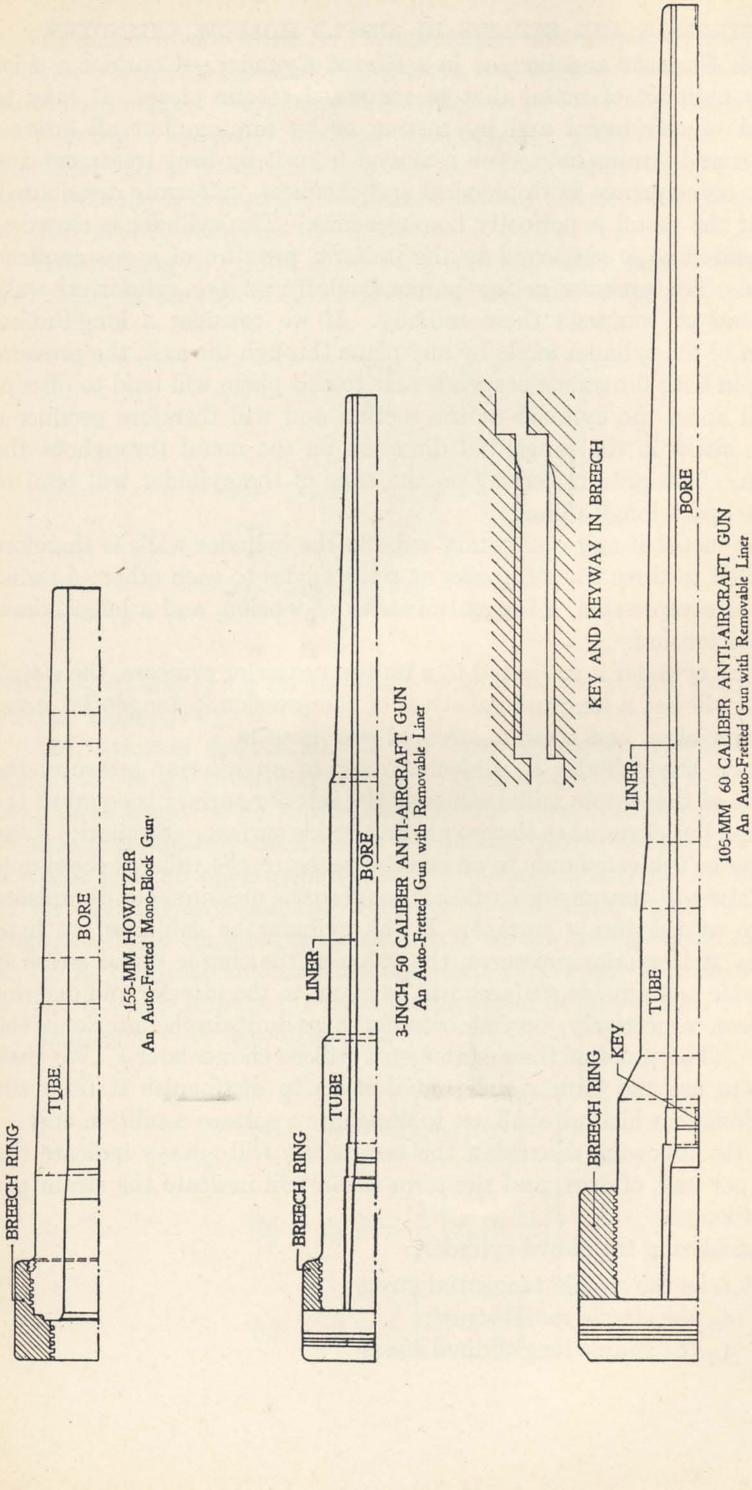
In addition to the self-hooping effect produced during the process of cold working, the physical qualities of the metal are altered considerably. The metal of the cylinder has been stressed beyond its elastic limit and we have seen that overstrain in gun steels, when followed by proper heat treatment, raises the elastic limit and the tensile strength and decreases the toughness and ductility. These changes are a maximum at the bore and a minimum at the exterior surface.

The combined effect of the increased elastic limit and the residual compression of metal near the bore is such as nearly to double the elastic strength pressure of the gun.

Three guns constructed by the process of cold-working, or autofrettage, are shown in Fig. 57. The great simplification introduced by this construction is evident.

Loose Liners and Monobloc Construction.—Each of the two antiaircraft guns shown consists of a cold-worked tube and a loose liner, with a breech ring threaded on to the rear of the tube. A *loose liner* is made to such dimensions that, when assembled in the gun, there is a small but definite clearance between the outside surface of the liner and the inside surface of the tube. In addition to its clearance in the tube, the liner is made with a slight taper to facilitate its assembly and removal. Two shoulders prevent the forward movement of the liner in the tube. Two positioning keys near the breech end (at the origin of the rifling) prevent the rotation of this member under the counter action of the projectile. The keys, diametrically opposite each other, are made integral with the liner and beveled on the forward end. The keyways in the tube are longer than the keys so as to allow for the lengthening of the liner during firing. Liner retaining rings (not shown) are used to prevent liners from backing out.

The 155-mm. howitzer shown in the figure is of monobloc construction, that is, made of one piece with no liner. This method of construction is now in more favor than the loose-liner construction. The entire gun can be replaced quickly and easily in the field, and the original cost of the one-piece gun is considerably less than the cost of the two-piece weapon.



155-MM HOWITZER
An Auto-Fretted Mono-Block Gun

3-INCH 50 CALIBER ANTI-AIRCRAFT GUN
An Auto-Fretted Gun with Removable Liner

105-MM 60 CALIBER ANTI-AIRCRAFT GUN
An Auto-Fretted Gun with Removable Liner

FIG. 57.

STRESSES AND STRAINS IN SIMPLE HOLLOW CYLINDERS

155. Stresses and Strains in a Closed Cylinder.—Consider a thick hollow cylinder of metal that is composed of one piece. It may be formed of any metal and by casting or by forging, but all internal stresses and strains have been removed from it by heat treatment and all the constituents, both physical and chemical, uniformly distributed, so that the metal is perfectly homogeneous. The cylinder is closed at both ends and is subjected to the uniform pressure of a gas confined within. The pressure acting perpendicularly on the cylindrical walls will tend to compress them radially. If we consider a longitudinal section of the cylinder made by any plane through the axis, the pressure acting in both directions perpendicular to this plane will tend to disrupt or pull apart the cylinder at the section and will therefore produce a tensile stress in the tangential direction on the metal throughout the section. The pressure acting on the ends of the cylinder will tend to pull it apart longitudinally.

The metal of any elementary cube in the cylinder walls is therefore subjected to three *simple stresses* at right angles to each other: a radial stress of compression, a tangential stress of tension, and a longitudinal stress of tension.

If the cylinder is subjected to a uniform exterior pressure, the *simple stresses* will be: a longitudinal stress of compression, a tangential stress of compression, and a radial stress of compression.

When the cylinder is subjected only to an interior pressure, the amount of the simple radial stress at the interior surface is equal to the pressure, but diminishes to zero at the outside surface. Similarly, if the cylinder be subjected only to an exterior pressure, the value of the simple radial stress at the outside surface is equal to the pressure, but diminishes to zero at the inside surface. If the cylinder be subjected to both interior and exterior pressures, the value of the simple radial stress at the inside and outside surfaces will be equal to the interior and exterior pressures, respectively, varying between these limits in the interior of the metal. (The proof of these statements will be shown later.) We shall therefore use the term *simple radial stress* to distinguish it from the term *pressure* which we shall use to designate a surface condition only.

In the following discussion the term *stress* will always indicate the stress per unit of area, and the term *strain* will indicate the strain per unit of length.

Considering the above cylinder,

Let s_t be the simple tangential stress;

s_p, the simple radial stress;

s_q, the simple longitudinal stress

at any point in the cylinder. Numerically, strains will be considered positive when they represent elongations, and negative when they represent shortenings. Tensions will be taken as positive and compressions as negative. To avoid dealing with negative powder pressures, all pressures will be considered as positive. The simple radial stress (s_p) being actually a pressure, as explained before, will be taken as positive when it acts to compress the metal.

Substituting s_t, s_p, and s_q for s_x, s_y, and s_z, respectively, in Eqs. (1), and changing the sign of s_p in accordance with our convention, we get:

$$\left.\begin{aligned} &(a) \quad e_t = \frac{1}{E}\left[s_t + \frac{s_p}{3} - \frac{s_q}{3}\right] \\ &(b) \quad e_p = -\frac{1}{E}\left[s_p + \frac{s_q}{3} + \frac{s_t}{3}\right] \\ &(c) \quad e_q = \frac{1}{E}\left[s_q - \frac{s_t}{3} + \frac{s_p}{3}\right] \end{aligned}\right\} \qquad (2)$$

where e_t, e_p, and e_q are the resultant tangential, radial, and longitudinal strains, respectively.

156. Stresses and Strains in An Open Cylinder.—If the cylinder considered in the preceding section be open at both ends, it is obvious that there could be no simple longitudinal stress. Although a gun is neither a completely open nor a completely closed cylinder, we shall consider it as an open cylinder for it acts more nearly in this manner. If we assigned any probable value to s_q, the effect would be almost negligible. By considering s_q equal to 0, we are acting on the safe side as far as the resultant tangential stress is concerned, and, as we shall see later, this is usually the determining factor in gun design.

Letting $s_q = 0$, Eqs. (2) become

$$\left.\begin{aligned} &(a) \quad e_t = \frac{1}{E}\left[s_t + \frac{s_p}{3}\right] \\ &(b) \quad e_p = -\frac{1}{E}\left[s_p + \frac{s_t}{3}\right] \\ &(c) \quad e_q = \frac{1}{E}\left[\frac{s_p}{3} - \frac{s_t}{3}\right] \end{aligned}\right\} \qquad (3)$$

By making certain assumptions under the theory of elasticity,* it can be shown that

$$s_p = -A + \frac{B}{r^2} \tag{4}$$

$$s_t = A + \frac{B}{r^2} \tag{5}$$

in which equations A and B are constants to be determined, and r the radius to any point under consideration.

Let P_0 be the unit pressure acting on the interior of the cylinder;
P_1, the unit pressure acting on the exterior of the cylinder;
R_0, the interior radius of the cylinder;
R_1, the exterior radius of the cylinder.

Since the simple radial stress s_p at R_0 and at R_1 is equal to the pressures P_0 and P_1, respectively, we have

$$\left.\begin{aligned} (a)\quad P_0 &= -A + \frac{B}{R_0^2} \\ (b)\quad P_1 &= -A + \frac{B}{R_1^2} \end{aligned}\right\} \tag{6}$$

Solving Eqs. (6) for the constants A and B, we have

$$\left.\begin{aligned} (a)\quad A &= \frac{P_0R_0^2 - P_1R_1^2}{R_1^2 - R_0^2} \\ (b)\quad B &= \frac{R_0^2R_1^2}{R_1^2 - R_0^2}(P_0 - P_1) \end{aligned}\right\} \tag{7}$$

157. Fundamental Equations of Gun Construction.—Substituting values of A and B in Eqs. (4) and (5) above, we get for the *simple stresses* at distance r:

$$s_p = -\left[\frac{P_0R_0^2 - P_1R_1^2}{R_1^2 - R_0^2}\right] + \left[\frac{R_0^2R_1^2(P_0 - P_1)}{R_1^2 - R_0^2}\right]\frac{1}{r^2} \tag{8}$$

$$s_t = \left[\frac{P_0R_0^2 - P_1R_1^2}{R_1^2 - R_0^2}\right] + \left[\frac{R_0^2R_1^2(P_0 - P_1)}{R_1^2 - R_0^2}\right]\frac{1}{r^2} \tag{9}$$

* For a more detailed derivation of these equations, see Love "Theory of Elasticity," and Fuller and Johnson "Applied Mechanics."

For *resultant stresses* at distance r:

Substituting the above values of s_p and s_t in Eqs. (3), and multiplying by E, we get

$$S_t = Ee_t = \frac{2}{3}\left[\frac{P_0R_0^2 - P_1R_1^2}{R_1^2 - R_0^2}\right] + \frac{4}{3}\left[\frac{R_0^2R_1^2(P_0 - P_1)}{R_1^2 - R_0^2}\right]\frac{1}{r^2} \quad (10)$$

$$S_p = Ee_p = \frac{2}{3}\left[\frac{P_0R_0^2 - P_1R_1^2}{R_1^2 - R_0^2}\right] - \frac{4}{3}\left[\frac{R_0^2R_1^2(P_0 - P_1)}{R_1^2 - R_0^2}\right]\frac{1}{r^2} \quad (11)$$

$$S_q = Ee_q = -\frac{2}{3}\left[\frac{P_0R_0^2 - P_1R_1^2}{R_1^2 - R_0^2}\right] \quad (12)$$

These five equations are the fundamental equations of gun construction on which all others are based. They may be used in any case where the reduced equation (to be developed later) is not available. Equation (8) gives the simple radial stress existing in the metal at any radius r due to the pressures P_0 and P_1. A careful examination will show that s_p is always positive, that is, always a *compressive* stress; and it varies between the limits of P_0 at the inside surface to P_1 at the outside surface.

Equation (9) gives the simple tangential stress at the radius r when the pressures P_0 and P_1 are acting. A negative value for s_t means that this stress is compression instead of tension.

Equations (10), (11), and (12) give, respectively, the tangential, radial and longitudinal resultant stresses caused by P_0 and P_1. It must be remembered that these stresses are only hypothetical. What actually exists is a state of strain whose components in the respective directions are e_t, e_p, and e_q. It is convenient to multiply each of these components by the modulus of elasticity E, and refer to the resulting products, S_t, S_p, and S_q as *resultant stresses.* Positive values of these quantities denote tension and negative values compression.

As brought out in a preceding section, failure is considered to occur when the actual strain at any point exceeds the strain at the elastic limit as determined by ordinary tensile and compressive tests; or, what is the same thing, when the resultant stress at any point exceeds the elastic limit. That is, for safety we must have S_t, S_p, and S_q numerically equal to or less than θ or ρ, the elastic limits of the metal in tension and compression respectively.

Subscripts will be added to our adopted symbols to indicate the particular condition assumed to exist. For example, S_{tP_0} indicates the resultant tangential stress due to an interior pressure only. Similarly,

$S_{tP_0R_0}$ indicates the same condition when $r = R_0$; and $P_{0\theta}$, accordingly, represents the interior pressure to produce a resultant stress of θ.

In any simple homogeneous cylinder forming a part of a cannon, we have three cases to consider. There may be a pressure on the interior of the cylinder and none on the exterior, the atmospheric pressure being considered zero. There may be a pressure on the exterior of the cylinder and none on the interior. Or, both exterior and interior pressures may be acting at once, the interior pressure usually being greater. We will consider the simple cylinder under these circumstances.

158. First Case: Interior Pressure Only.—This is the case of a gun consisting of a single piece, or of the jacket or outside hoops of a built-up gun. Making $P_1 = 0$, we get from Eqs. (10), (11), and (12):

$$S_{tP_0} = \frac{2}{3}\left[\frac{P_0R_0^2}{R_1^2 - R_0^2}\right] + \frac{4}{3}\left[\frac{P_0R_0^2R_1^2}{R_1^2 - R_0^2}\right]\frac{1}{r^2} \tag{13}$$

$$S_{pP_0} = \frac{2}{3}\left[\frac{P_0R_0^2}{R_1^2 - R_0^2}\right] - \frac{4}{3}\left[\frac{P_0R_0^2R_1^2}{R_1^2 - R_0^2}\right]\frac{1}{r^2} \tag{14}$$

$$S_{qP_0} = -\frac{2}{3}\left[\frac{P_0R_0^2}{R_1^2 - R_0^2}\right] \tag{15}$$

Since S_{tP_0} in Eq. (13) is positive for any value of r, the resultant tangential stress is one of tension throughout the cylinder. S_{tP_0} has its highest value when r has its least value, or when $r = R_0$. The resultant tangential stress is therefore greatest at the inside surface of the cylinder, decreasing as we proceed outward and reaching its least value at the outside surface of the cylinder where $r = R_1$.

Similarly, since S_{pP_0} is negative for all values of r, Eq. (14) shows that the resultant radial stress is one of compression throughout the cylinder. It has its highest numerical value when $r = R_0$, and its least numerical value when $r = R_1$, showing that the resultant radial stress, like the resultant tangential stress, is greatest at the inside and least at the outside surface of the cylinder.

159. Graphical Representation of Resultant Stresses.—In order to show clearly the variations of stress through the walls of a cylinder, a method of graphical representation is used. Consider a set of coordinate axes RR and SS as shown in Fig. 58. Distance along the R-axis represents radial distance measured from the inner surface of the cylinder, the radius R_0 being taken as the origin. Distance along the S-axis represents stress, tension (positive values) being plotted above the R-axis and compression (negative values) below.

As an example, consider the simple cylinder where

$$R_0 = 2 \text{ in.}$$

$$R_1 = 6 \text{ in.}$$

and

$$P_0 = 36{,}000 \text{ lb. per sq. in.}$$

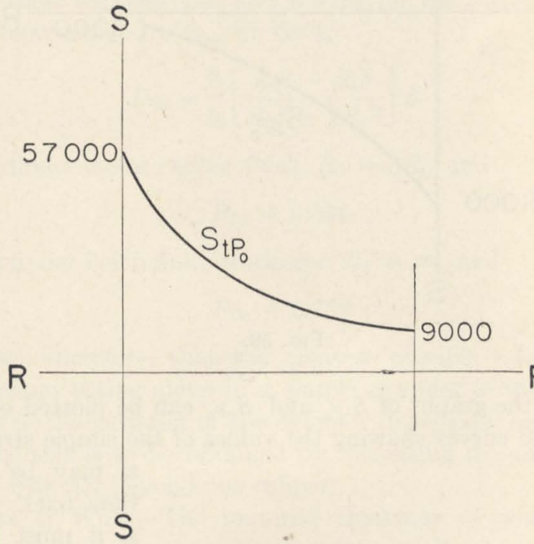


FIG. 58.

To determine the resultant tangential stress at the outside surface: Let $r = R_1$, and R_0, R_1, and P_0 equal the values given. Substituting in Eq. (13) we get

$$S_{tP_0R_1} = +\ 9000 \text{ lb. per sq. in. (tension)}$$

At the inside surface, taking the same values for R_0, R_1, and P_0, but putting $r = R_0$, we get

$$S_{tP_0R_0} = +\ 57{,}000 \text{ lb. per sq. in. (tension)}$$

Similarly a number of intermediate points might be plotted by substituting the appropriate values for r. The points could be joined by a smooth curve, as shown in the figure, giving a graphical representation of the stress acting throughout the cylinder. Regardless of values taken for pressure and radii, the graph of this resultant tangential stress will always be concave upward.

A graph of resultant radial stress in the same cylinder is shown in

Fig. 59. The values are obtained from Eq. (14) by making the same substitutions as above. The graph of resultant radial stress is concave downward.

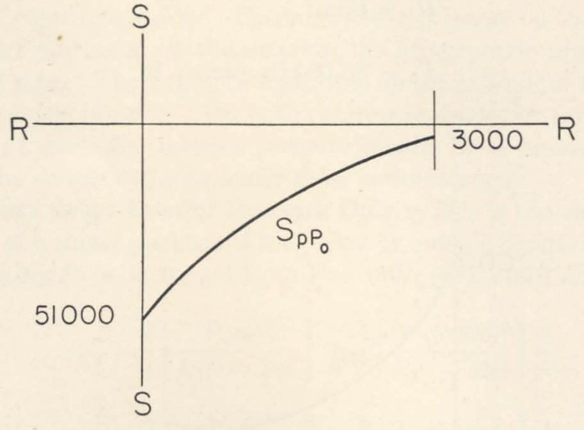


FIG. 59.

If desired, the graphs of S_{tP_0} and S_{pP_0} can be plotted on the same axes. Likewise curves showing the values of the simple stresses s_t and s_p may be plotted on these axes. In plotting s_p it must be remembered that the positive sign indicates compression. It is therefore plotted below the R-axis. Figure 60 shows plots of s_t and s_p for the cylinder under consideration.

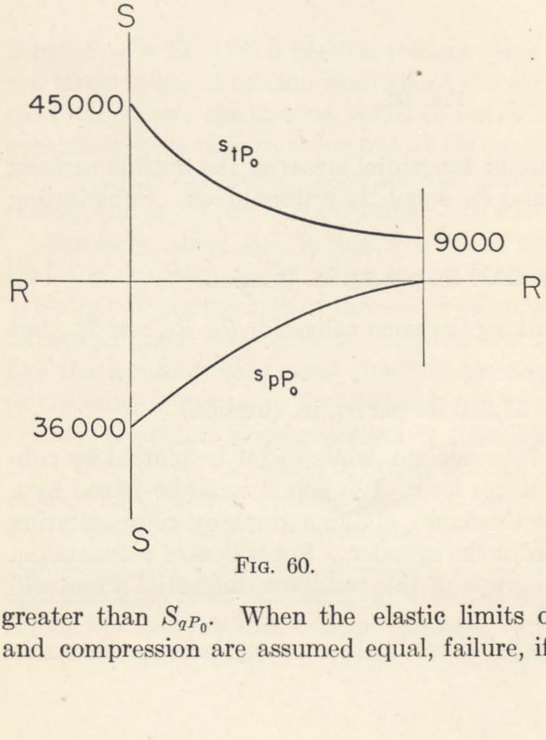


FIG. 60.

160. Limiting Values of Interior Pressure Acting Alone.—The equations show that, at any point in the section, S_{tP_0} is always greater than S_{pP_0} and that the latter is equal to or greater than S_{qP_0}. When the elastic limits of the metal for tension and compression are assumed equal, failure, if it occurs, will therefore

be due to the highest value of S_{tP_0}, shown to be at the inside surface of the cylinder, exceeding numerically the elastic limit, θ, for tension.

The limit of safe interior pressure will, therefore, be given by Eq. (13) under the following assumptions,

$$r = R_0,\ S_{tP_0} = S_{tP_0R_0} = \theta$$

Making these substitutions and solving for the corresponding value of P_0, now represented by $P_{0\theta}$, we have,

$$P_{0\theta} = \frac{3}{2}\left[\frac{R_1^2 - R_0^2}{R_0^2 + 2R_1^2}\right]\theta \tag{16}$$

If the cylinder is one caliber thick, $R_1 = 3R_0$, and

$$P_{0\theta} = 0.63\theta$$

If the cylinder has infinite thickness, $R_1 = \infty$, and

$$P_{0\theta} = 0.75\theta$$

It follows, therefore, that the greatest possible safe value for an interior pressure acting alone in a simple cylinder is three-fourths the elastic limit of the material of the cylinder in tension, and further that very little benefit is to be obtained by increasing the thickness of the walls of the cylinder beyond one caliber.

Thickness of Wall.—The required thickness of wall of cylinder, $R_1 - R_0$, to withstand a given interior pressure $P_{0\theta}$ in a cylinder with interior radius R_0, may be obtained by solving Eq. (16) for R_1 and then subtracting R_0. Its value is

$$R_1 - R_0 = R_0\left(\sqrt{\frac{3\theta + 2P_{0\theta}}{3\theta - 4P_{0\theta}}} - 1\right) \tag{17}$$

For a given interior pressure and elastic limit the thickness of wall is therefore proportional to the inside radius.

PROBLEMS

1. What is the maximum permissible interior pressure on a steel gun hoop, the interior diameter of which is 20 in. and the exterior diameter 28 in., the elastic limit of the metal being 60,000 lb. per sq. in.? Ans. 17,561 lb. per sq. in.

2. The steel tubes of a water-tube boiler are 2 in. in interior diameter and 2.4 in. in exterior diameter. The elastic limit of the metal is 30,000 lb. per sq. in. What is the limiting interior water pressure? Ans. 5103.2 lb. per sq. in.

3. Using a factor of safety of $1\frac{1}{2}$, what is the limiting interior pressure in a compressed air tank with interior and exterior diameter of 15 and 17 in. respectively? The elastic limit of the metal is 30,000 lb. per sq. in. Ans. 2391 lb. per sq. in.

4. The 6-in. wire-wound gun has the following dimensions at the powder chamber:

$R_0 = 4.5$ in., $R_1 = 12$ in. If the gun were constructed of a single forging with an elastic limit of 60,000 lb. per sq. in., what would be the maximum permissible powder pressure? Ans. 36,132 lb. per sq. in.

5. The cylinder of a hydraulic jack has an interior diameter of 10 in. and a maximum working pressure of 10,000 lb. per sq. in. What thickness of wall is required in order that the factor of safety may be $1\frac{1}{2}$? The elastic limit of the metal is 40,000 lb. per sq. in. Ans. 2.9 in.

161. Second Case: Exterior Pressure Only.—This is the case of the tube of a built-up gun while at rest. Making $P_0 = 0$, we get from Eqs. (10), (11), and (12):

$$S_{tP_1} = -\frac{2}{3}\left[\frac{P_1R_1^2}{R_1^2 - R_0^2}\right] - \frac{4}{3}\left[\frac{P_1R_0^2R_1^2}{R_1^2 - R_0^2}\right]\frac{1}{r^2} \tag{18}$$

$$S_{pP_1} = -\frac{2}{3}\left[\frac{P_1R_1^2}{R_1^2 - R_0^2}\right] + \frac{4}{3}\left[\frac{P_1R_0^2R_1^2}{R_1^2 - R_0^2}\right]\frac{1}{r^2} \tag{19}$$

$$S_{qP_1} = \frac{2}{3}\left[\frac{P_1R_1^2}{R_1^2 - R_0^2}\right] \tag{20}$$

Since S_{tP_1} is negative for all values of r, the resultant tangential stress is one of compression throughout the bore. The equation shows that its greatest numerical value is at the inside surface of the bore where $r = R_0$, and that its graph as a function of r is concave downward.

Making $r = R_0$ in Eq. (19),

$$S_{pP_1R_0} = \frac{2}{3}\left[\frac{P_1R_1^2}{R_1^2 - R_0^2}\right] \tag{21}$$

showing that the resultant radial stress at the inside surface of the cylinder is always one of tension. On the other hand, if we make $r = R_1$,

$$S_{pP_1R_1} = -\frac{2}{3}\left[\frac{P_1(R_1^2 - 2R_0^2)}{R_1^2 - R_0^2}\right] \tag{22}$$

which is positive when

$$R_1 < \sqrt{2}R_0$$

negative when

$$R_1 > \sqrt{2}R_0$$

and which vanishes when

$$R_1 = \sqrt{2}R_0$$

That is, the resultant radial stress at the outside surface of the cylinder may be either tension or compression, depending upon the relative values of R_0 and R_1.

Comparison of the values of $S_{pP_1R_0}$ and $S_{pP_1R_1}$ shows that the resultant radial stress of tension on the inside surface of the cylinder is always numerically greater than the resultant radial stress (compression or tension) on the outside surface.

The graph of S_{pP_1} as a function of r is concave upward.

The graphs of Eqs. (18) and (19) are shown plotted in Fig. 61 for $P_1 = 36{,}000$ lb. per sq. in. and $R_1 = 3R_0$.

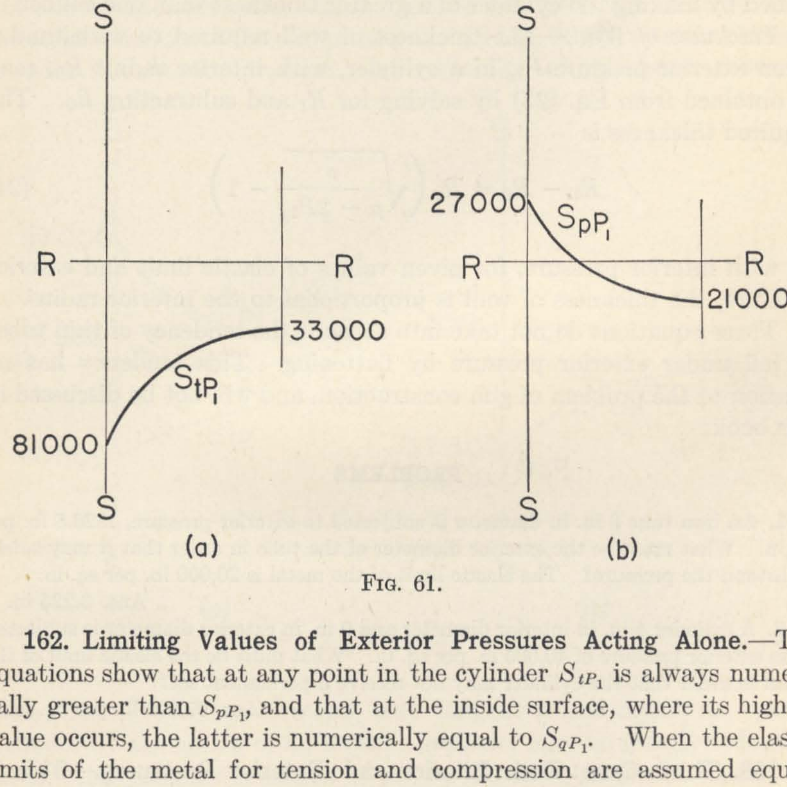


FIG. 61.

162. Limiting Values of Exterior Pressures Acting Alone.—The equations show that at any point in the cylinder S_{tP_1} is always numerically greater than S_{pP_1}, and that at the inside surface, where its highest value occurs, the latter is numerically equal to S_{qP_1}. When the elastic limits of the metal for tension and compression are assumed equal, failure, if it occurs, will therefore be due to the highest value of S_{tP_1}, shown to be at the inside surface of the cylinder, exceeding numerically the elastic limit ρ, for compression. The limit of safe exterior pressure will therefore be given by Eq. (18) under the following assumptions:

$$r = R_0, \quad S_{tP_1} = S_{tP_1R_0} = -\rho$$

Making these substitutions, and solving for P_1, now represented by $P_{1\rho}$, we obtain,

$$P_{1\rho} = \frac{1}{2}\left[\frac{R_1^2 - R_0^2}{R_1^2}\right]\rho \tag{23}$$

If the cylinder is one caliber thick,

$$R_1 = 3R_0 \quad \text{and} \quad P_{1_\rho} = 0.44\rho$$

If the cylinder has infinite thickness,

$$P_{1_\rho} = 0.50\rho$$

Here again it is seen that there is comparatively little advantage to be gained by making the cylinder of a greater thickness than one caliber.

Thickness of Wall.—The thickness of wall required to withstand a given exterior pressure P_{1_ρ} in a cylinder, with interior radius R_0, may be obtained from Eq. (23) by solving for R_1 and subtracting R_0. The required thickness is

$$R_1 - R_0 = R_0\left(\sqrt{\frac{\rho}{\rho - 2P_{1_\rho}}} - 1\right) \tag{24}$$

As with interior pressure, for given values of elastic limit and exterior pressure, the thickness of wall is proportional to the interior radius.

These equations do not take into account the tendency of thin tubes to fail under exterior pressure by flattening. This tendency has no relation to the problem of gun construction, and will not be discussed in this book.

PROBLEMS

1. An iron tube 3 in. in diameter is subjected to exterior pressure, 1326.5 lb. per sq. in. What must be the exterior diameter of the tube in order that it may safely withstand the pressure? The elastic limit of the metal is 20,000 lb. per sq. in.

Ans. 3.225 in.

2. A cylinder 4 in. in interior diameter and 9 in. in exterior diameter is subjected to an exterior pressure of 40,000 lb. per sq. in. What must be the elastic limit of the metal in order that the cylinder may not receive a permanent set?

Ans. 99,692 lb. per sq. in.

163. Third Case: Both Interior and Exterior Pressures.—This is the case of the tube, jacket, and hoops (except exterior hoops) of a built-up gun in action (while powder gas pressure is acting). The resultant tangential and radial stresses at any point of a given cross section may be calculated from Eqs. (10) and (11). The resultant longitudinal stress will always be either equal to or less than the resultant radial stress and is not calculated as part of this discussion. An inspection of these equations and Eqs. (13), (14), (18), and (19) will show that the total or *combined resultant stresses* are the algebraic sums of those set up by the given interior and exterior pressures considered as each acting alone. In Fig. 62 are shown the resultant stresses due to P_0 = 36,000 lb. per

sq. in. and P_1 = 18,000 lb. per sq. in. ($R_1 = 3R_0$), calculated by Eqs. (10) and (11). Figure 62 (*a*) shows the plot of tangential stresses and Fig. 62 (*b*) the plot of radial stresses. S_{tP_0} and S_{pP_0} are the resultant stresses due to P_0 alone, calculated from Eqs. (13) and (14), S_{tP_1} and S_{pP_1} are those due to P_1 alone, calculated from Eqs. (18) and (19). The algebraic sums of combined resultant stresses are S_t and S_p, respectively.

The positions of the curves of combined resultant stresses from interior and exterior pressures acting together will, of course, depend upon the relative values of the two pressures. In Fig. 62 the interior pressure is twice the exterior pressure. An inspection of this figure shows at

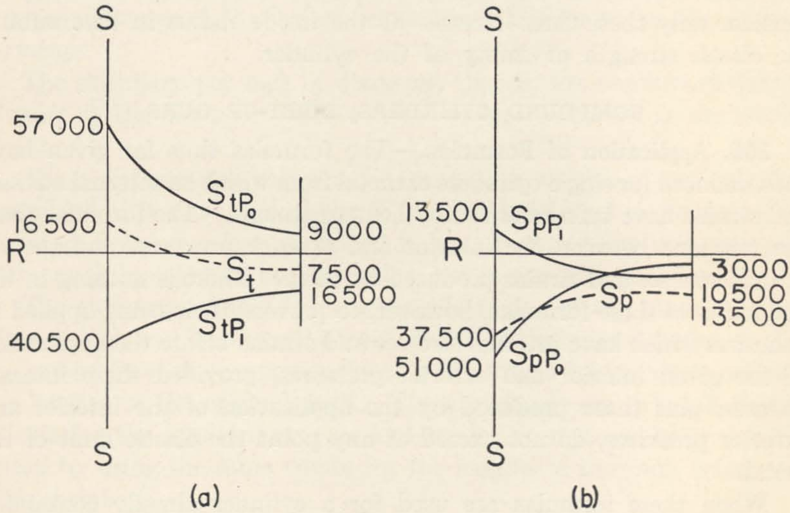


FIG. 62.

once that the resultant stresses, both tangential and radial, set up in a cylinder by the action of an interior pressure, may be greatly reduced if an exterior pressure is caused to act at the same time. Similarly, the resultant stresses caused by an exterior pressure may be reduced if an interior pressure is caused to act at the same time.

164. Point of Maximum Stress and Conditions for Safety.—We have observed (Figs. 60 and 61) that the resultant tangential stress and the resultant radial stress produced by either an interior or an exterior pressure acting alone are always numerically greatest at the inside surface of the cylinder. The resultant stresses produced by an interior pressure are generally opposite in sign from those produced by an exterior pressure. It follows that when both interior and exterior pressures act, the numerical values of the combined resultant stresses will

be highest at the inside or outside surface of the cylinder, depending upon the values of the interior and exterior pressures and upon the relative dimensions of the radii of the cylinder (Fig. 62).

By the application of Eqs. (10), (11), and (12) to a single cylinder of any dimensions, with any assumed values of P_0 and P_1, it can be shown that at the inside surface of the cylinder ($r = R_0$) there will be a combined resultant stress equal to or exceeding in numerical value any combined resultant stress at the outside surface of the cylinder ($r = R_1$). Further, this maximum resultant stress is always one of the following, depending on the values of P_0 and P_1: *tangential compression*, *tangential tension*, or *radial compression*. It is therefore necessary to consider only these three stresses at the inside radius in determining the elastic strength or safety of the cylinder.

COMPOUND CYLINDERS; BUILT-UP GUNS

165. Application of Formulas.—The formulas thus far given have been deduced for single cylinders of metal from which all internal stresses and strains have been removed by heat treatment. The formulas show the relations between the interior and exterior pressures and the resultant stresses and strains produced by them. There is nothing in the deduction of these formulas, however, to prevent their being applied to cylinders which have internal stresses and strains before the application of the given interior and exterior pressures, provided these internal stresses, plus those produced by the application of the interior and exterior pressures, do not exceed at any point the elastic limit of the metal.

When these formulas are used for a cylinder already containing internal stresses and strains, the deduced stresses and strains corresponding to any given set of interior and exterior pressures are not the total stresses and strains in the part of the cylinder considered, but are only those produced by the applied internal and external pressures. In order to obtain the total resulting stresses and strains, the new stresses and strains must be added algebraically to those already existing in the cylinder at the point under consideration.

It has been shown that the resistance of a cylinder to an interior pressure may be greatly increased by the application of pressure on the exterior surface. This is accomplished in practice by shrinking one or more cylinders over the first, causing a uniform exterior pressure to be exerted on the outer surface of the inner cylinder or tube.

Cylinders built up in this way are known as compound cylinders. They may be considered as simple cylinders containing internal stresses and strains caused by the shrinkage. As stated, the formulas deduced

for simple cylinders are applicable to compound cylinders in so far as finding the resultant stresses and strains produced by interior and exterior pressures alone is concerned. We need only to consider the compound cylinder as a simple cylinder and apply Eqs. (10), (11), and (12). To obtain the total resultant stresses, we must add algebraically to the resultant stresses from the above formulas those caused by the successive shrinkage of the cylinders.

166. Shrinkage Calculations.—The process of assembling two or more cylinders to form a compound cylinder or built-up gun is known as *shrinkage.*

The difference between the exterior diameter of the tube and the interior diameter of the jacket before heating is known as the *absolute shrinkage.*

The shrinkage per inch of diameter, that is, the absolute shrinkage divided by the diameter of the contact surface, is known as the *relative shrinkage.*

The radial pressure between the contacting surfaces of two cylinders assembled by shrinkage, and due to the shrinkage alone, is known as the *shrinkage pressure.* It is expressed in pounds per square inch, and acts with equal intensity on both cylinders but in opposite directions.

The shrinkage diminishes the outside radius of the inner cylinder, after cooling, and increases the inside radius of the outer cylinder, so that the radius R_1 of the contact surfaces is of a length intermediate between the lengths of the original radii. The shrinkages are so small that in calculating the resultant stresses and strains no material error is introduced by using the same values for the lengths of the radii before and after shrinkage.

The strain per unit of circumference at the outer surface of the tube and the inner surface of the jacket caused by shrinkage may be obtained by dividing the resultant tangential stresses at these surfaces by E. Since the circumference is proportional to the diameter, the values give the relative shrinkages of the two cylinders and, when multiplied by the diameters, the changes in length of the two diameters. The sum of these is the absolute shrinkage.

The method used in the calculation of simple shrinkage, is illustrated in the following example:

A gun tube having radii of 2 in. and 4 in. is composed of metal having an elastic limit of 50,000 lb. per sq. in. It is calculated that the interior powder pressure acting alone would produce a maximum resultant tangential stress (S_t) of 70,000 lb. per sq. in. at the inner fiber of the tube.

(*a*) What shrinkage pressure will be necessary at the outside surface of the tube to reduce S_t to the elastic limit?

(*b*) What will be the *relative shrinkage* of the tube?

(*c*) What will be the decrease in the outside diameter of the tube?

(*d*) The jacket is 3 in. thick and composed of the same type metal. What will be the increase in the inside diameter of the jacket?

(*e*) What will be the absolute shrinkage?

Solution:

(*a*) An exterior or shrinkage pressure must be applied on the tube that will produce, at rest, a compressive stress of 70,000 − 50,000 = 20,000 lb. per sq. in., since 50,000 lb. per sq. in. is the elastic limit of the metal.

Substitute in Eq. (18):

$$S_t = -20,000 \text{ lb. per sq. in.}$$
$$r = R_0 = 2 \text{ in.}$$
$$R_1 = 4 \text{ in.}$$

and solve for P_1.

$P_1 = 7500$ lb. per sq. in. shrinkage pressure. Thus, with the specified powder pressure, the elastic limit in tension will be exactly reached in action if the shrinkage pressure on the tube is 7500 lb. per sq. in.

(*b*) To determine the relative shrinkage of the tube, we must first determine the resultant tangential stress produced at the outside radius by the shrinkage pressure.

Substitute in Eq. (18):

$$P_1 = 7500 \text{ lb. per sq. in.}$$
$$R_0 = 2 \text{ in.}$$
$$r = R_1 = 4 \text{ in.}$$

Solving, we get: $S_t = -10,000$ lb. per sq. in. (compression)

Then: $S_t = Ee_t$, or $e_t = \dfrac{10,000}{30,000,000} = 0.000333$ in. per in. (relative shrinkage)

(*c*) The outside diameter of the tube is reduced by: (diameter) × (relative shrinkage) = 8.0 × 0.000333 = 0.0027 in., nearly

(*d*) The resultant tangential stress at the inside of the jacket due to the shrinkage pressure may be found from Eq. (13) by considering the jacket alone, and substituting:

$$P_0 = 7500 \text{ lb. per sq. in.}$$
$$r = R_0 = 4 \text{ in.}$$
$$R_1 = 7 \text{ in.}$$

Solving, we get:

$$S_t = 17,270 \text{ lb. per sq. in. (tension)}$$

Then $e_t = \dfrac{17,270}{30,000,000} = 0.000576$ in. per in. relative shrinkage

The inside diameter of the jacket is increased by:

$$8 \times 0.000576 = 0.004608 \text{ in.}$$

(*e*) The absolute shrinkage = 0.004608 + 0.0027 = 0.0073 in. That is, the inside diameter of the jacket before assembly must be made 0.0073 in. smaller than the outside diameter of the tube.

167. Practical Application of Formulas to a Built-up Gun.—

Let S_{tP_g} = Resultant tangential stress at any radius r, due to action of powder gas pressure only.

S_{tP_s} = Resultant tangential stress at any radius r, due to the shrinkage pressure only.

S_{tP_a} = Resultant tangential stress at any radius r, when gun is in action, that is both powder gas pressure and shrinkage pressure acting.

At a certain section of a built-up gun, composed of a tube and jacket, the radii are:

$$R_0 = 3 \text{ in.}$$
$$R_1 = 5 \text{ in.}$$
$$R_2 = 8 \text{ in.}$$

The powder pressure in the bore at this section is 40,000 lb. per sq. in. The elastic limit for tube and jacket is 50,000 lb. per sq. in.

(*a*) Determine the resultant tangential stress (S_{tP_g}) at each surface due to the *powder gas pressure* alone.

(*b*) Assuming that the jacket is to be stressed to the elastic limit tangentially when the gun is in *action*, determine the resultant tangential stress (S_{tP_a}) at each surface under this condition.

(*c*) Determine also the resultant tangential stress (S_{tP_s}) at the same points, due to the *shrinkage pressure*.

(*d*) Plot the graphs of these stresses.

(*e*) Is the gun safe radially?

Solution: It is evident that we shall be concerned with three cylinders with radii as shown in Fig. 63.

(*a*) To determine the stress which is set up by the powder gas pressure only, consider the tube and jacket combined, and subjected only to the powder pressure.

Using Eq. (13) with $P_0 = 40{,}000$, $r = R_0 = 3$, and $R_1 = 8$, we can determine this stress at the *inner* surface by solving for S_t.

$$S_t = \frac{2}{3}\left[\frac{40{,}000 \times 9}{55}\right] + \frac{4}{3}\left[\frac{40{,}000 \times 9 \times 64}{55}\right] \times \frac{1}{9}$$

$$= 66{,}425 \text{ lb. per sq. in. (T)}$$

To determine the stress at the *outer* surface due to powder pressure only, use the same equation and the same data, except $r = R_1 = 8$.
Solving for S_t, we get

$$S_t = 13{,}091 \text{ lb. per sq. in. (T)}$$

At the common surface, by substituting $r = 5$ in the same equation, we get

$$S_t = 26{,}706 \text{ lb. per sq. in. (T)}$$

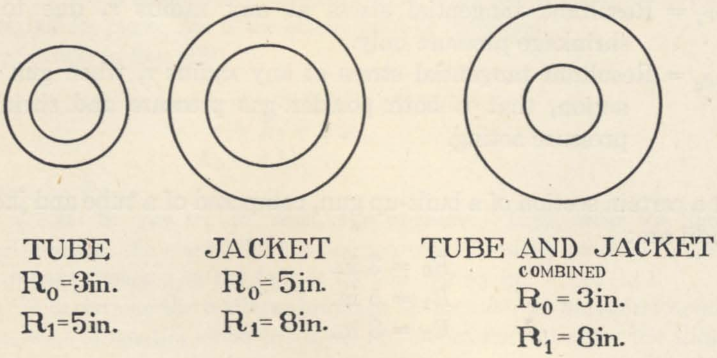


FIG. 63

The curve showing these stresses is plotted in Fig. 64, marked S_{tP_g}.

(*b*) When the gun is in action the inner fiber of the jacket is to be stressed tangentially to the elastic limit. To determine the *in-action* pressure P_a existing at this surface, consider the jacket only and in Eq. (13) substitute $S_t = 50{,}000$; $r = R_0 = 5$; $R_1 = 8$; and solve for P_0.

$$P_0 = P_a = 19{,}118 \text{ lb. per sq. in.}$$

The *in-action* stress (S_{tP_a}) at the *outer* fiber of the jacket may be determined by considering the jacket with an interior pressure P_a only acting. In Eq. (13) substitute $P_0 = 19{,}118$; $R_0 = 5$; $r = R_1 = 8$; and solve for S_t.

$$S_{tP_a} = 24{,}510 \text{ lb. per sq. in. (T)}$$

The *in-action* stress at the outside surface of the tube may be obtained by considering the tube with an exterior pressure of 19,118 lb. per sq. in. and also subjected to the interior powder pressure. In Eq. (10) substitute $P_0 = 40{,}000$; $P_1 = 19{,}118$; $R_0 = 3$, $r = R_1 = 5$; and solve for S_t.

$$S_{tP_a} = 10{,}748 \text{ lb. per sq. in. (T)}$$

The *in-action* stress at the *inside* surface of the tube may be obtained by using the same equation and the same data, except $r = R_0 = 3$. Solving for S_{tP_a} at the inside surface of tube, we get

$$S_{tP_a} = 38{,}590 \text{ lb. per sq. in. (T)}$$

All the *in-action* tangential stresses have now been determined and are plotted in Fig. 64, marked S_{tP_a}.

(*c*) A part of the *in-action* pressure of 19,118 lb. per sq. in. at the common

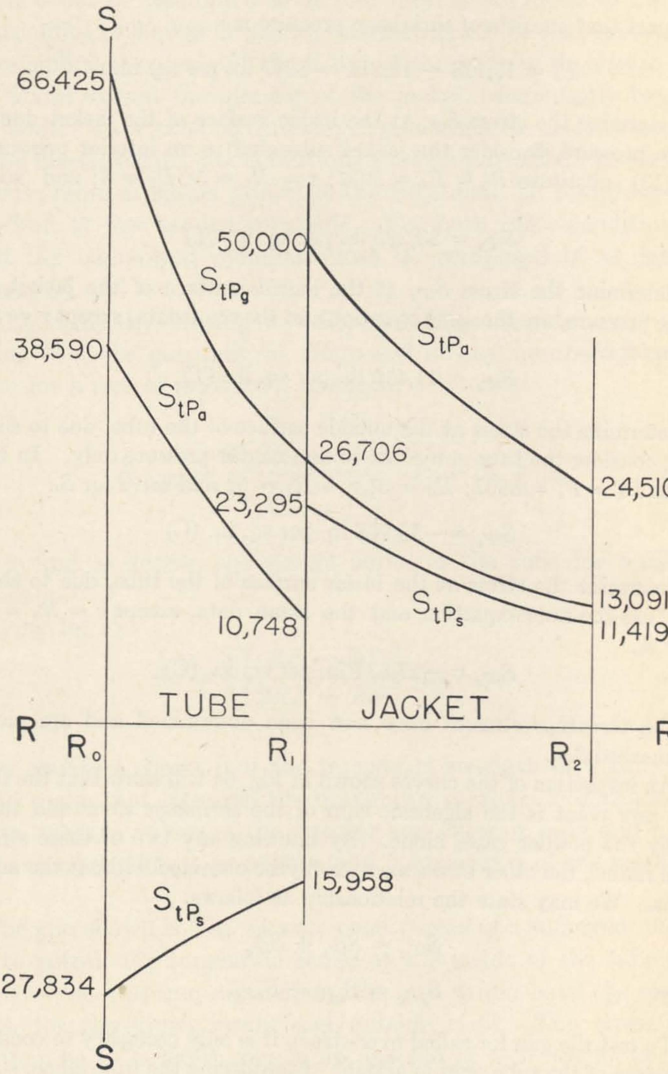


FIG. 64.

surface is due to the effect of the powder gas pressure P_g and part is due to the shrinkage pressure P_s. To determine the part due to powder pressure only, consider the tube and jacket combined and subjected only to the interior powder

pressure. In Eq. (8) substitute $P_0 = 40{,}000$; $P_1 = 0$; $R_0 = 3$; $r = 5$; $R_1 = 8$; and solve for s_p, the simple radial stress.

$$s_p = P_g = 10{,}211 \text{ lb. per sq. in.}$$

The part that consists of shrinkage pressure is

$$P_s = 19{,}118 - 10{,}211 = 8907 \text{ lb. per sq. in.}$$

To determine the stress S_{tP_s} at the inside surface of the jacket due to this shrinkage pressure, consider the jacket subjected to an interior pressure only. In Eq. (13) substitute $P_0 = P_s = 8907$; $r = R_0 = 5$; $R_1 = 8$; and solve for S_t.

$$S_{tP_s} = 23{,}295 \text{ lb. per sq. in. (T)}$$

To determine the stress S_{tP_s} at the *outside* surface of the jacket, due to shrinkage pressure, use the same equation and the same data, except $r = R_1 = 8$; and solve for S_t.

$$S_{tP_s} = 11{,}419 \text{ lb. per sq. in. (T)}$$

To determine the stress at the outside surface of the tube, due to shrinkage pressure, consider the tube subjected to an exterior pressure only. In Eq. (18) substitute $P_1 = P_s = 8907$; $R_0 = 3$; $r = R_1 = 5$; and solve for S_t.

$$S_{tP_s} = -15{,}958 \text{ lb. per sq. in. (C)}$$

To determine the stress at the *inside* surface of the tube, due to shrinkage pressure, use the same equation and the same data, except $r = R_0 = 3$; and solve for S_t.

$$S_{tP_s} = -27{,}834 \text{ lb. per sq. in. (C)}$$

All the *shrinkage* stresses have now been determined and are plotted in Fig. 64, marked S_{tP_s}.

(*d*) An inspection of the curves shown in Fig. 64 will show that the *in-action stress* at any point is the algebraic sum of the *shrinkage stress* and the stress caused by the powder gases alone. By knowing any two of these stresses at the same radius, the other stress may readily be obtained without the use of the equations. We may state the relationship as follows:

$$S_{tP_a} = S_{tP_s} + S_{tP_g}$$

Similarly

$$S_{pP_a} = S_{pP_s} + S_{pP_g}.$$

(*e*) To test the gun for radial over-stress, it is only necessary to consider the inside surface of the tube, gun in action. Considering the tube alone, subjected to interior powder pressure and exterior pressure P_a, in Eq. (11) substitute $P_0 = 40{,}000$; $P_1 = P_a = 19{,}118$; $r = R_0 = 3$; $R_1 = 5$; and solve for S_p.

$$S_{pP_a} = -48{,}420 \text{ lb. per sq. in. (C)}$$

As the elastic limit is 50,000 lb. per sq. in., the gun is safe.

168. Elastic Strength of Built-up Guns.—It will be noticed in Fig. 64, which shows the curves of stress for a two-layer gun, that the metal of the bore is not stressed to the elastic limit in action or at rest. The two cylinders could be assembled so as to compress the metal of the bore to its elastic limit of 50,000 lb. per sq. in. at rest, but in that case a powder pressure sufficient to extend the metal of the bore to its elastic limit in action would extend the interior of the jacket tangentially beyond its elastic limit. In a two- or three-layer gun whose parts have essentially the same elastic limits, the conditions that all parts shall be strained to the elastic limit in action and that the tube shall be compressed to its elastic limit at rest are incompatible. For both these conditions to be fulfilled the compound cylinder must be composed of at least four cylinders.

In Eq. (13), by placing $r = R_0$, and $R_1 = R_n$ (the outer radius), assuming that the gun may be composed of any number of cylinders, we have for a gun of maximum strength,

$$S_{tP_0R_0} = \frac{2}{3}\left[\frac{2R_n^2 + R_0^2}{R_n^2 - R_0^2}\right] P_0 = \theta_0 + \rho_0 \tag{25}$$

where θ_0 and ρ_0 denote the elastic limits of the tube for tension and compression.

Solving for P_0

$$P_0 = \frac{3}{2}\left[\frac{R_n^2 - R_0^2}{2R_n^2 + R_0^2}\right](\theta_0 + \rho_0) \tag{26}$$

This equation shows that the tangential strength of a gun, so built up as to make that strength the maximum possible, is dependent only upon the relative values of the interior and exterior radii and upon the sum of the elastic limits in tension and compression of the metal of the tube.

If the gun shown in Fig. 64 were constructed of a sufficient number of layers to permit the tangential stress at the inside of the tube to vary between $-\rho$ at rest and θ in action, the gun would have the maximum strength for the given inside and outside radii. The stress at rest would then be $-50{,}000$ lb. per sq. in. instead of $-27{,}834$ lb. per sq. in., and from Eq. (26) P_0 could be increased from 40,000 lb. per sq. in. to approximately 60,000 lb. per sq. in. As stated, this is only possible when the gun is composed of four or more concentric members. Otherwise, in working the tube to its elastic limit at rest and in action, outer members would be stressed beyond the elastic limit in action.

COLD-WORKED GUNS; CENTRIFUGALLY CAST GUNS

169. Condition of Cylinder during Cold-working.—For all values of the wall ratio used in gun construction, it has been shown that, with interior pressure only acting, the resultant tangential stress is greater than the resultant stresses in the radial or longitudinal direction. The stress plots developed in this section, therefore, will show only the values of the resultant tangential stress.

The distribution of the stresses in the walls of a cylinder, during the application of cold-working pressure, cannot be computed by the usual equations which apply only below the elastic limit. The stress distribution, however, can be closely approximated from special measurements showing the strains existing at various radii, and from the new elastic limit found in samples taken from various sections of the wall. A typical distribution of the stress during application of the cold-working pressure is shown by curve (*a*) in Fig. 65. It will be noted that the stress at every section of the cylinder exceeds the original elastic limit of the metal indicated by the line θ.

170. Condition of Cylinder after Cold-working.—Upon removal of the hydraulic pressure, the cylinder remains in a permanently enlarged condition. The elastic limit has been raised throughout the cylinder. The increase in elastic limit for a given percentage of cold-working will vary with different compositions of steel.

The new elastic limit, θ', will coincide approximately with the stress developed during cold-working, which is indicated by the curve (*a*) of Fig. 65.

The metal of the cylinder also contains internal stresses called *residual stresses*. The metal near the bore is in a state of compression and that near the outside surface is in a state of tension. Curve (*b*) in Fig. 65 shows a typical distribution of the residual stresses through the wall of a cold-worked cylinder. For complete equilibrium, the curve must cross the axis of zero stress at some point, S_0, and the area between the tension branch of the curve and the axis must equal the area between the compression branch and the axis.

This residual stress corresponds to the shrinkage stress in the cylinders of a built-up gun at rest. In fact, a cold-worked gun will have the same distribution of residual stress as would be found in a gun built up of an infinite number of layers.

171. Stresses in a Cold-worked Gun in Action.—We have seen that the actual stresses in a built-up gun in action are the algebraic sum of the stresses due to shrinkage (residual stresses in a cold-worked gun) and those due to the powder pressure. Exactly the same principle

holds true for the cold-worked gun. With this relationship we can plot a curve showing the maximum allowable stress due to powder pressure only, which will be required to stress the cold-worked gun to its new elastic limit θ'. This curve is indicated by (c) in Fig. 65, and is the algebraic difference between the curve showing θ' and the curve (b) of residual stresses. The cold-worked cylinder should stand without failure any stress due to interior pressure alone, which does not exceed at any point the stress indicated by curve (c). In computing stresses in cold-worked guns due to powder pressure, the equations developed earlier in the chapter are applicable because the metal is perfectly elastic within its new elastic limit.

172. Elastic Strength of Cold-worked Guns.—A thick-walled cylinder which has been cold-worked, and then properly heat-treated, will withstand, without failure, the subsequent application of any bore pressure which does not exceed the pressure applied to accomplish the cold-working. In general the elastic strength pressure is almost doubled. Of this increase, about half is due to the increase in the elastic limit and the other half to the residual stress condition. A typical cylinder before cold-working has an elastic strength pressure of 45,000 lb. per sq. in., and after cold-working it is increased to 80,000 lb. per sq. in.

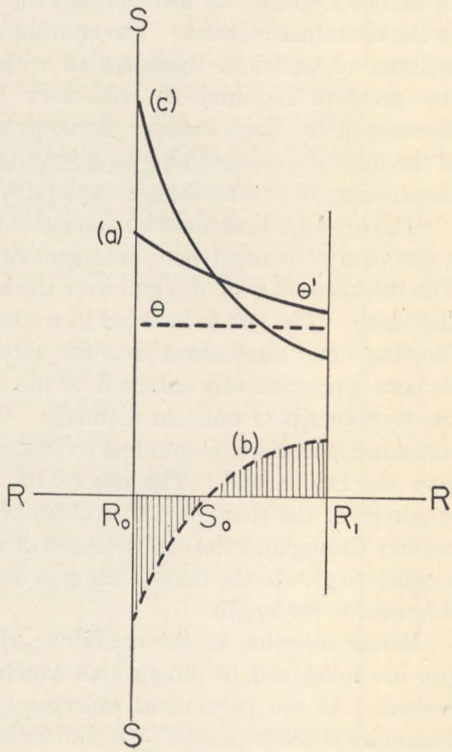


FIG. 65.

The auto-fretted cylinder must be machined to finished dimensions. Removal of metal from the bore and from the exterior affects the residual stress condition, decreasing the benefits to some extent. Also a suitable factor of safety must be applied. A finished gun made from the cylinder mentioned, after making the proper allowances, would have a maximum permissible pressure of 48,000 lb. per sq. in. for the cold-worked gun and 26,000 lb. per sq. in. for the same gun not cold-worked.

173. Manufacture of Cold-worked Guns.—The process consists essentially in taking a single cylinder with the interior diameter slightly less than the caliber desired and subjecting it to an interior hydraulic pressure of from about 44,000 to more than 100,000 lb. per sq. in. (depending upon the wall ratio and the elastic limit of the metal), permanently expanding the cylinder by the desired amount.

After extensive experimenting at the Watertown Arsenal, the Ordnance Department has adopted the method of cold-working known as the container method. The container is simply an outer member or cylinder of sufficient thickness to withstand, without permanent set, the pressure required to cold-work the forging contained therein. Because of the large exterior diameter necessary for the container, and of the difficulty of obtaining long forgings of such diameters, it is usually constructed of several lengths securely fastened together.

The pressure that must be applied in the bore of a cylinder to produce a specified permanent bore enlargement is a function of the wall ratio. The thickness of wall of a gun over the breech is much greater than over the chase. The gun is inserted in a container, the interior of which has the shape and dimensions that the exterior of the gun is to have after its bore is permanently enlarged by the desired amount. The outside of the container is of uniform diameter. The thickness of the wall of the container, therefore, is greatest over the muzzle of the gun and is least over the breech end. The use of the container enables the pressure required for the thickest wall section of the gun to be applied simultaneously throughout the entire length of the bore of the gun and makes it possible to give to the bore of the gun a uniform permanent enlargement throughout its length.

Before insertion in the container, the bore and the exterior of the gun are machined to dimensions which the process increases to those desired. As the permanent enlargement of the interior and exterior diameters is accompanied by a shortening of the gun, allowance is made for this longitudinal contraction.

The layout of cold-working equipment is shown diagrammatically in Fig. 66.

The gun to be cold-worked is placed within the container, packed with high-pressure packing, and held in place by a cross-rail and tie-rod assembly and suitable centering pieces. Filler pieces of steel and wood are inserted in the bore to reduce the volume of high-pressure water.

The high pressure is developed in two stages. Ordinary commercial apparatus is used in the first or low-pressure stage. This consists essentially of a pump, pressure gage, and suitable piping. The low-pressure water is pumped to an intensifier where the high pressure is developed.

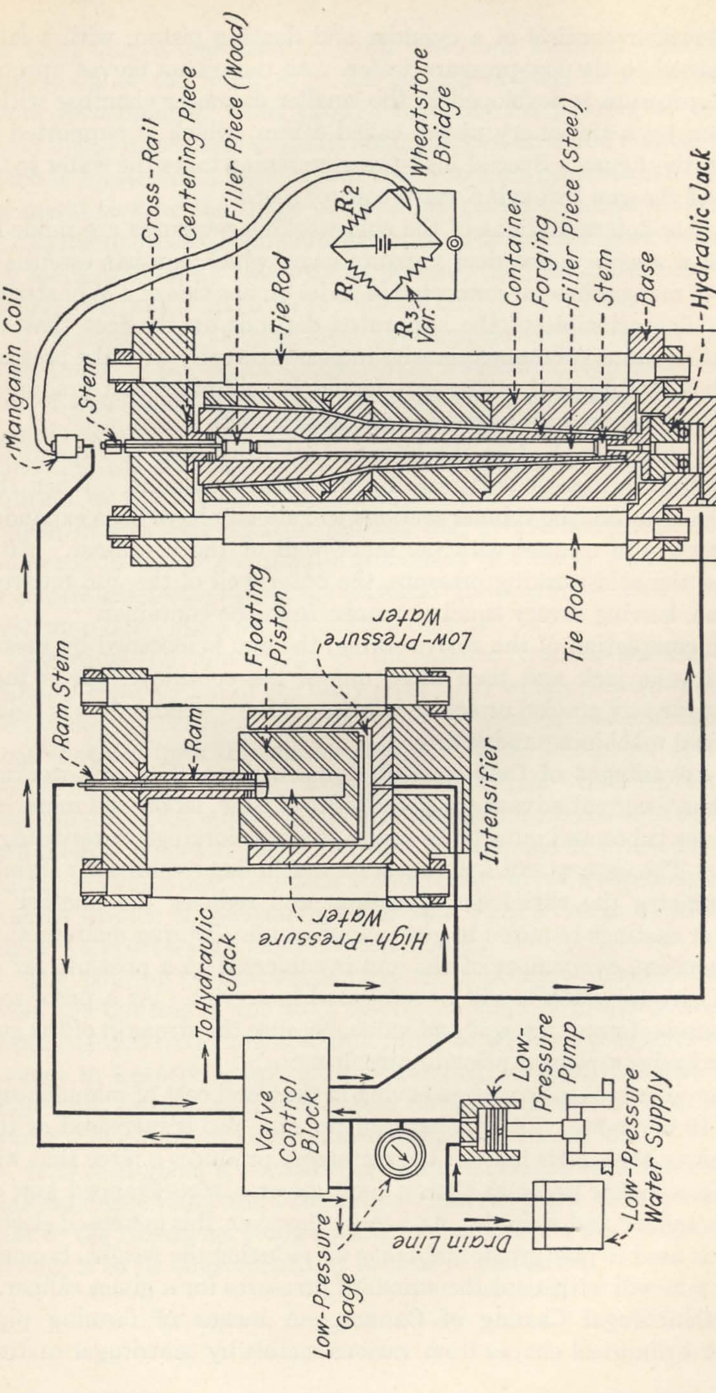


FIG. 66.—Layout of Cold-working Equipment.

This intensifier consists of a cylinder and floating piston, with a large area exposed to the low-pressure water. As the piston moves upward, the high pressure is developed in the smaller diameter chamber within the piston by a stationary piston called a ram, which is supported as shown in the figure. Special high-pressure piping takes the water to the interior of the gun through a valve-control block.

Accurate determinations of the cold-working pressures are made by means of a sensitive electrical pressure gage, which consists essentially of a coil of manganin wire connected in series on one side of a Wheatstone bridge. The principle of the apparatus depends on the fact that the electrical resistance of manganin wire increases directly with the pressure to which it is subjected. The instrument is calibrated and graduated to read pressure directly in pounds per square inch.

The pressure applied to the bore is that calculated to expand the section with the highest wall ratio by the desired amount. When this pressure is reached, the thinner sections will already have been expanded until they are in contact with the inner wall of the container. After release of the cold-working pressure, the outer wall of the gun recovers somewhat, leaving a very small clearance from the container.

Upon completion of the cold-working, the gun is loosened by means of a hydraulic jack and then lifted out of the container. It is then inspected for any cracks, or other defects. After "soaking," it is ready for the final machining and rifling.

174. Advantages of Cold-worked Construction.—The cold-working process has the great advantage of economy of time, labor, and material, and enables tubes and guns to be made of single forgings or centrifugal castings. The process saves the accurate machining required for shrinkage, eliminates the shrinkage operation, and reduces the number of forgings or castings required in gun manufacture. During manufacture by this process, every fiber of the gun is subjected to a pressure far in excess of any to which it will be subjected in service. As a proof test this feature is of great interest and value, because the strength of the gun has actually been proved prior to any firing.

The process makes possible a saving in time and cost of manufacture of 25 to 40 per cent. The efficiency of the gun also is increased as the process raises the elastic limit of the metal and produces a piece that will withstand a higher pressure than a built-up or a wire-wrapped gun of the same caliber and weight. As a rule, however, this increased elastic strength is used to give greater mobility by reducing the weight, because a lighter gun will withstand the standard pressures for a given caliber.

175. Centrifugal Casting of Cannon.—A means of forming pipe and other cylindrical shapes from various metals by centrifugal casting

has been known and used for more than one hundred years, but the application of this process to the casting of steel is a comparatively recent development. The process involves the pouring of molten or liquid metal into a chill mold (a mold made of cast iron instead of sand), which is rotated at a high rate of speed so that centrifugal force causes the metal to take the shape of the mold before it solidifies. Since the solidifying or freezing temperature of steel is much higher than that of any metal previously cast by this process, the problem of centrifugally casting steel was a much more difficult one.

This method of shaping steel has been developed by the Ordnance Department to the extent that it is now a standard step in the manufacture of gun tubes up to and including the 3-in. antiaircraft. Experimental castings for 5-in. guns have been produced and studies are being made towards producing guns up to 8-in. caliber by this method. In addition to the saving of time and money, elimination of the forging process in gun manufacture relieves one of the serious problems encountered in the production of armament in time of war. The action of centrifugal forces upon the physical and chemical structure of the steel, moreover, gives a high-quality casting.

Knowing the dimensions of the desired cannon casting and the chemical composition of the alloy steel from which it is to be cast, the steel melter determines the weights of the various items of the melting stock that will form the furnace charge. When the "heat" is ready, the molten steel is poured into a special runner box which carries a spout that will direct the molten metal into the opening in the chill mold. The chill mold is a special shaped casting, the outside of which fits into the casting machine but the inside is bored out to the desired shape of the exterior surface of the cannon to be cast. Each design of tube or liner requires a special chill mold for that design.

The pouring of the whole heat must be accomplished quickly to avoid the freezing of the steel before the mold is properly filled. The casting is removed from the chill mold as soon as it is solid and rigid enough to keep its shape during handling. When removed from the chill mold, the hot casting is cooled slowly in cinders or in a furnace to obtain a more uniform crystalline structure of the metal.

It is then given a normalizing and annealing treatment, and rough-machined internally and externally. The casting is then quenched and drawn, the treatment being similar to that given a gun forging. If the casting is to be cold-worked, it is then re-machined.

RIFLING

176. General Considerations.—Rifling consists of a number of helical grooves cut in the bore of a gun, beginning in front of the powder chamber and extending to the muzzle. The lands are the surfaces of the bore between the grooves. The purpose of rifling is to impart to elongated projectiles the rotation necessary to insure stability in flight. The projectile is constructed with one or more rotating bands of soft metal, slightly larger in diameter than the bore of the gun. As the projectile moves down the bore under the action of the powder gases, the lands cut through the rotating band, engraving it to conform to the cross section of the bore, and causing rotation of the projectile. The ribs of metal from the band projecting into the grooves prevent the escape of gas past the projectile.

The driving edge of the land is the side which exerts the pressure against the rotating band causing rotation. Its shape is an important design feature. The non-driving edge is of less importance.

The *twist of rifling* at any point is the inclination of a groove to the element of the bore. It may be uniform, increasing, or a combination of the two. It is usually expressed in terms of the number of calibers of length in which the groove completes one complete turn, for example, one turn in 40 calibers.

In *uniform twist*, the degree of twist is constant from the origin of rifling to the muzzle, the path of the groove being a uniform spiral. In *increasing twist*, the degree of twist increases from zero or some small value, for example one turn in 50 calibers, at the origin to a sharper twist at the muzzle, such as one turn in 25 calibers. The *rate* of increase may be uniform or become more rapid. Certain designers have employed the increasing twist to a point several calibers from the muzzle and uniform twist from there on.

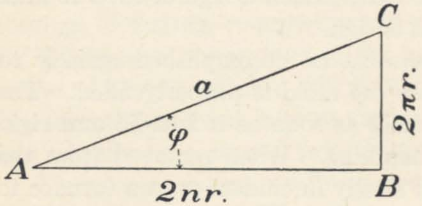


Fig. 67.

Rifling is specified by the developed curve of the groove. For uniform twist, the developed curve is a straight line as indicated by a in Fig. 67. In increasing twist, the form of the curve is parabolic.

Let ϕ be the angle of twist;
n, the twist in calibers;
r, the radius of the bore in feet.

We then have for uniform twist rifling

$$\tan \phi = \frac{2\pi r}{2nr} = \frac{\pi}{n} \tag{27}$$

for the value of the tangent of the angle of twist. For rifling with increasing twist ϕ is variable, but the value of its tangent at any point is $\frac{\pi}{n}\cdot$

Relation between the Velocity of Translation and the Velocity of Rotation of the Projectile.—

Let v be the velocity of translation of the projectile at any point of the bore in feet per second;
ϕ, the angle of twist of the rifling at the same point;
ω, the angular velocity of the projectile at the same point in radians per second.
d, the diameter of the bore in feet.

The linear velocity of rotation of a point on the outside surface of the projectile is evidently $v \tan \phi$.

The angular velocity is therefore

$$\omega = \frac{2v \tan \phi}{d} \tag{28}$$

Knowing the muzzle velocity and the twist at the muzzle, the velocity of rotation of the projectile as it leaves the gun may be determined.

177. Design Factors.—Standard rifling design practice is based upon theoretical computations of forces and stresses, experimental tests, data from service firings, and practical manufacturing considerations. Influencing factors include the following.

Ballistics.—The system of rifling and the angle of twist selected depend both upon the gun and the projectile and must be such that with the established muzzle velocity the necessary rotation will be imparted to a projectile of a given design to insure its stability in flight. The type of fuze used may dictate the maximum velocity of rotation permitted.

Strength.—The number, width, and profile of the lands must be such as to withstand the stresses set up as the projectile passes through the bore. The type and twist of rifling should develop stresses on both gun and projectile which are within allowable limits.

Wear.—The accuracy life of a weapon depends primarily on the condition of the rifling. The degree of wear is affected by the type and

twist employed, and by the width, number, depth, and form of the lands and grooves. In one instance the accuracy life of a gun of a certain design was doubled by decreasing the degree of uniform twist, increasing the width of lands and depth of grooves, and decreasing the number of lands and grooves.

178. Considerations as to Type and Twist of Rifling.—The primary consideration is that the projectile should emerge from the muzzle with the proper rotational velocity. The characteristics of both the gun and the projectile are involved. Under-spin will result in tumbling and instability of flight. In over-spin, the longitudinal axis of the projectile will tend to retain its same position during flight, not adapting its direction to the curved line of flight, and thus not insuring head-on impact.

Both the uniform and the increasing systems of twist have their advantages; their relative merits require an evaluation of all factors. Both systems have been employed, and are found in weapons in current use in our service. However, the uniform twist is now specified for U. S. Army guns under construction.

Comparing the two systems, it is apparent that, to produce the same rotational velocity at the muzzle, the use of increasing twist will result in less driving force on the driving side of the land (and on the rotating band) near the origin of rifling and at the point of maximum powder pressure and projectile acceleration than if uniform twist is used, but at the muzzle this will be reversed. However, if the rate of increase of twist is properly selected, the maximum stress on the lands (and on the rotating band of the projectile) will be less with increasing twist than with uniform twist. The danger of stripping the rotating band from the projectile is thus reduced by use of the increasing twist, but this advantage has been minimized by the development of modern progressive-burning powders, with properly selected granulation, which permit attainment of the desired muzzle velocity with lower maximum pressures.

With the uniform twist, the rotating band is engraved initially to the exact form which will be maintained throughout the length of travel in the bore and there is no subsequent displacement of band metal. With increasing twist, however, there is a continuous change in the angle of the grooves engraved in the band, with continuous displacement of metal. Initially the grooves are approximately parallel to the axis of the projectile, but, as the twist of rifling increases, they must conform to this constantly changing angle. The resulting disadvantages of the increasing twist are (1) concentration of driving pressure on the forward part of the band, with high unit pressure on the driving edge of the land,

(2) increased friction, abrasion, and temperature, and (3) higher value for total passive resistance although the starting resistance is less. Rifling with increasing twist increases manufacturing costs somewhat.

The apparent advantages of the uniform twist over the increasing is reflected in the present general tendency of all countries to specify the former type. There are sufficient proponents of the use of increased twist, however, and sufficient weapons in service so rifled, to warrant further study of this type.

179. Developed Curve of Increasing Twist Rifling.—If the twist increases from zero at the breech uniformly to the muzzle, the equation of the developed curve of the rifling will be of the form

$$y = ax + bx^2 \tag{29}$$

which being differentiated twice gives

$$\frac{d^2y}{dx^2} = 2b$$

That is, the rate of change in the tangent to the groove is constant.

A twist in this form would offer less resistance than the uniform twist to the initial rotation of the projectile. But, to diminish this resistance still further, a twist that is at first less rapid than the uniformly increasing twist and later more rapid has been frequently adopted for rifled guns. The equation of the semi-cubic parabola

$$x^{3/2} = 2py \tag{30}$$

is generally adopted for the developed curve of rifling with increasing twist. The twist is assumed at breech and muzzle and the curve between these points is obtained from the above equation.

The tangent to the curve at any point makes with the axis of x an angle whose tangent is dy/dx. The value of the tangent of the angle at any point is π/n, Eq. (27), n representing the twist in calibers, the number of calibers in which the groove makes a complete turn.

Therefore, differentiating Eq. (30),

$$\frac{dy}{dx} = \tan \phi = \frac{3x^{1/2}}{4p} = \frac{\pi}{n} \tag{31}$$

Exercise **1.**—Determine the equation of the developed rifling curve, and the part of the curve to be used, for a 3-in. gun having a twist of 0 at the breech end, 1 turn in 25 calibers at a point 12.52 in. from the muzzle, and from this point uniform to the muzzle. The length of the rifled bore is 72.72 in.

The twist at the breech is 0, or one turn in an infinite number of calibers. Therefore n in Eq. (31) is infinite, $\tan \phi$ is 0 and $x = 0$; and from Eq. (30) y is also 0. The origin of the curve is therefore at the breech.

At 12.52 in. from the muzzle, $x = 72.72 - 12.52 = 60.2$, and the twist $n = 25$.

Substituting these values in Eq. (31) and solving for p,

$$p = \frac{3(60.2)^{1/2}25}{4\pi} = 46.31$$

Substituting in (30) we have for the equation of the developed groove of the rifling from the breech to a point 12.52 in. from the muzzle

$$x^{3/2} = 92.62y$$

and the part of the curve to be used lies between the origin and the ordinate for which the abscissa is $x = 60.2$. From this point to the muzzle the curve is a straight line making with the axis of x an angle whose tangent is $\pi/25$.

The curve is shown numbered 1 in Fig. 68.

Exercise **2.**—Determine the equation of the developed rifling curve, and the part of the curve to be used, for the 4.7-in. Armstrong gun, 50 calibers long. The twist is 1 turn in 600 calibers at the breech, and 1 turn in 30 calibers at the muzzle. The length of the rifled bore is 203.12 in.

At the breech $n = 600$ and $\tan \phi = \pi/600$.
At the muzzle $\tan \phi = \pi/30$.

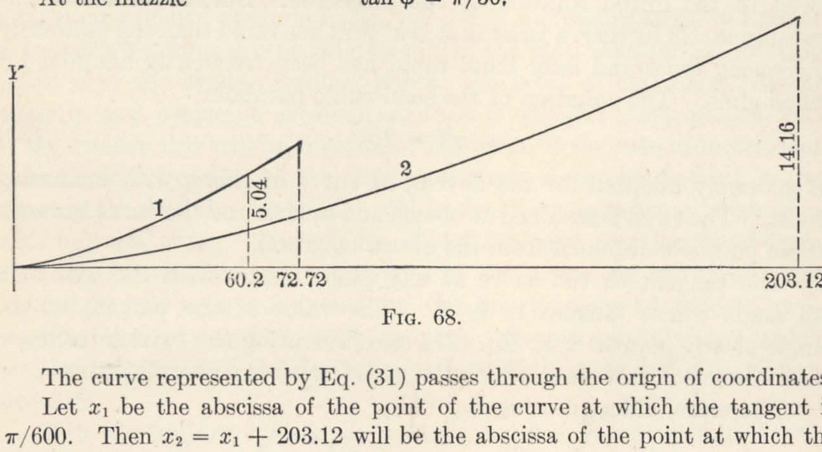


FIG. 68.

The curve represented by Eq. (31) passes through the origin of coordinates.

Let x_1 be the abscissa of the point of the curve at which the tangent is $\pi/600$. Then $x_2 = x_1 + 203.12$ will be the abscissa of the point at which the tangent is $\pi/30$.

From Eq. (31).

$$\frac{\pi}{600} = \frac{3x_1^{1/2}}{4p}, \qquad \frac{\pi}{30} = \frac{3(x_1 + 203.12)^{1/2}}{4p}.$$

We have two equations involving x_1 and p. Solving we find

$$p = 102.2 \qquad x_1 = 0.51 \qquad x_2 = 203.63$$

The equation of the developed curve of the rifling is, Eq. (30),

$$x^{3/2} = 204.4y$$

and the abscissae of the extremities of the part of the curve to be used are the values determined for x_1 and x_2.

The curve is shown numbered 2 in Fig. 68.

180. Form of Profile of Rifling.—Examples of various rifling cross sections are shown in Fig. 69. The number, width, and depth of grooves increase with the caliber of the weapon. The type and twist of rifling also influence the design. The greater the number of grooves and the less the twist, the narrower can be the lands and the shallower the grooves, as the unit pressure on the driving edges will be less. Shallow grooves weaken the bore less than deeper ones, and the broader the grooves are in comparison with the lands, the less will be the resistance to engraving. On the other hand, a gun with fewer and wider lands, and deeper grooves, will have a longer accuracy life, retaining for a greater number of rounds, as erosion progresses, its ability to impart to the projectile the desired velocity and rotation.

The width of lands should be sufficient to give the necessary strength to withstand the stresses set up on the driving edge. The depth and form of the grooves must be such that the unit pressures on the land and band are not excessive, and are exerted in the desired direction. The lands must not be so narrow that the localized high temperature due to friction will produce excessive erosion.

The driving edge of the land should be substantially straight and radial in direction in order that the stress may be exerted tangentially. Rounding of corners facilitates manufacture and, at the bottom, is necessary for strength to prevent the development of cracks. The shape of the non-driving edge is less important, so long as the requisite strength is insured.

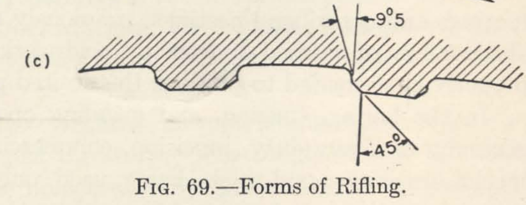


FIG. 69.—Forms of Rifling.

(*a*) A form previously used.
(*b*) Present standard for guns under 6 in.
(*c*) Present standard for guns over 6 in.

Figure 69 (*a*) shows the form of rifling ~~formerly~~ employed in the 155-mm. gun and other weapons. (Viewed from muzzle end.) The driving edge is radial and its bottom rounded. Difficulty of machining the groove with one edge straight and the other rounded has led to the adoption of a different form. Figure 69 (*b*) shows the type now standard

for guns under 6 in. in caliber. The sides of the lands are radial and symmetrical, with bottoms rounded for strength and to facilitate manufacture. Figure 69 (*c*) illustrates the rifling now standard in guns from 6 in. to 16 in. in caliber. It is essentially the same as that employed for smaller weapons except that, on account of the increased depth of grooves, the side walls are not radial but are cut on a $9°.5$ taper, and the top corners are chamfered, to reduce tool wear and the tearing of the sidewalls during the rifling operation.

PROBLEMS

1. The twist of the rifling in a 6-in. gun is one turn in 50 calibers at the breech and one turn in 25 calibers at the muzzle. The muzzle velocity is 2600 ft. per sec. What is the velocity of rotation of the projectile?

2. In the above gun the increasing twist begins at the origin of rifling and extends for a length of 208 in. and the developed curve of rifling is a semi-cubic parabola. Determine its equation.

THE MANUFACTURE OF GUNS

The finishing of guns involves various boring, turning, reaming, and grinding operations on thick hollow cylinders in preparing them for assembly and in working them to final form and dimensions, their assembly, and the rifling of the finished bore. As previously indicated in the discussion of gun construction, the number of component cylinders depends upon the design and, to a certain extent, the caliber; developments in physical and mechanical metallurgy have made possible the use of fewer members and, within certain limits, of the monobloc type of construction. All assembly is by shrinkage except in those weapons for which a loose liner has been prescribed to facilitate replacement in the field.

The material employed in the gun factory consists chiefly of steel forgings and centrifugal castings, previously rough-machined to within about 0.3 in. of finished dimensions, cold-worked (when prescribed), and properly heat-treated to produce the desired physical qualities.

In the boring, turning, and grinding operations the equipment is generally of heavy duty, precision, commercial types used in industry, special machines and tools being used only where necessary. The rifling operation requires special equipment.

181. Sequence of Operations.—The finishing of a typical gun involves the following operations: (1) telltaling, (2) rough boring of interiors, (3) rough turning and finish turning or grinding of exteriors, (4) step boring and taper reaming of interiors that are to be assembled over other members, (5) assembly by shrinkage, (6) finish boring of

innermost member, (7) finish boring and reaming of powder chamber, and (8) rifling of bore. Before assembly of two members, the outer member is finished to include (4) and the inner member to include (3); after each assembly the exterior of the assembly must be refinished if other members are to be added. The innermost member is added to the assembly last, and operations (6), (7), and (8) are performed only after assembly is complete.

Telltaling is done in an engine lathe and is for the purpose of balancing the stock to secure the most advantageous distribution of metal for the subsequent boring operations. At this stage, also, cylindrical bearing surfaces are turned on the exterior, on which the work will be supported in *steady rests* for boring.

Rough boring is done in an engine lathe, using a packed bit or series of such tools, and leaving sufficient stock for finish boring. The tools cut from both ends towards the center in order to minimize errors caused by long tool travel.

For *exterior* work, the cylinder is mounted on expanding plugs centered in the rough bore. Rough and finish turning is done in the lathe, but finishing may be performed in a cylindrical grinder. If the piece being worked is to become the inner member of a shrinkage assembly, the exterior finishing must be within precise limits with relation to the dimensions and form of the inner surface of the outer member.

When the inner diameters of outer members are to be tapered from breech to muzzle to facilitate assembly, the operation consists first in cutting a series of cylindrical zones, progressively smaller in diameter. This *step boring* operation is performed with packed bits. A series of tapered reamers, including roughing and finishing sets, is then used to blend the various zones into a continuous conical surface of the desired accuracy and finish. Since each reamer cannot progress further through the work than its diameter permits, a set of various sizes is necessary, for example six for the 3-in. M3 gun, the combined length of which exceeds the length of the cylinder by an amount sufficient to provide an overlap at each junction.

Assembling by shrinkage requires no machining other than the operations required to handle the work. The rough bore of the inner member is threaded at the breech and muzzle for the lifting plug and water plugs, and lugs for lifting are provided on the outer member to facilitate handling.

Finish boring is performed on the bore after the assembly is complete or, in loose liners and monobloc guns, after all exterior work has been done. The operation is performed clear through the bore from the breech end, using packed bits. The powder chamber is then bored to

size and shape, and finished by the use of special roughing and finishing reamers which conform to the size and contour of the prescribed chamber.

The final operation on the gun, or loose liner, is *rifling* the bore. The rifling machine controls only the twist of the grooves and the travel of the rifling bar. The number, spacing, and shape of the grooves is controlled by cutters in the special rifling head; for small caliber cannon each passage through the bore results in a finishing cut the whole width of the groove, and from 0.0005 in. to 0.0025 in. in depth. The rate of travel of the cut is about 8 ft. per minute, and the operation is performed from the muzzle end so that irregularities at the beginning of the rifling will be in the excess length of the work which is finally cut off and discarded.

Investigation is being made of the possibility of broaching the rifling with a tool similar in general type to the solid broach now used for small splined holes. In this event the twist of the rifling will be built into the broach. Whereas rifling heads now in use have tools for only one-half or one-fourth the number of grooves to be cut, and consequently must be indexed radially to complete the operation, the broach will cut all the grooves at one time. Several broaches may be needed to give proper depth and form, but each broach would complete its portion of the work in one pass. A special machine of extremely rugged design would be required. The method has been applied successfully to small arms barrels.

182. Gun Lathe.—This machine is essentially a heavy duty engine lathe in which the tailstock has been replaced by the boring bar and its

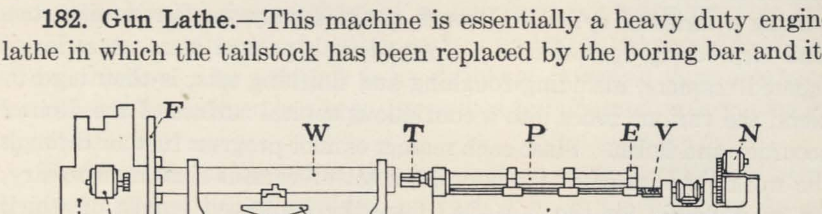


FIG. 70.

driving mechanism (Fig. 70). The boring bench O may be adjusted along the bed B for different lengths of work, or may be replaced by the conventional tailstock when used for turning.

In operation, the work W is mounted in steady rests S and S', and clamped in jaws on the faceplate F. The work is rotated at the selected speed through gearing in the headstock H which transmits power from the main drive motor M to the faceplate. A feed screw in

the bed, also driven from the headstock gearing, imparts motion to the side carriage C for external finishing. A shaft extending from the headstock to gearing at the rear of the boring bench may be used to drive the bar feed screw V unless a separate motor N is provided. This bar feed screw moves the rear bar support E along the bench, thus advancing the bar, without rotation, for internal finishing.

Some machines are arranged so that external and internal work may be performed simultaneously. In this case, the work is rotated at the proper speed for turning, while the bar is rotated at a speed differing sufficiently from that of the work to give proper surface speed for boring. This method has been used successfully in roughing operations.

Consideration has been given to a design of boring lathe in which the driving mechanism is located at the center of the bed, replacing steady rest S'. The work is held and driven in a revolving steady rest instead of a faceplate. This design appears to offer the advantages of simpler operation and control, as well as adaptability to varying lengths of work, although it is less adaptable to varying diameters.

183. Vertical Boring Mill.—Cylindrical parts in which the axis is short in relation to the diameter are usually finished on a machine which is essentially a lathe standing on its headstock end (Fig. 71). The table T holds and drives the work as does the lathe faceplate. Vertical supports V carry side heads S for exterior finishing, and provide mounting for the cross rail R. Several types of standard machines are available. The boring mill is usually equipped with two bar supports and boring bars B, which may be set vertically or at an angle, and are fed down into the work for internal finishing. If desired, the bar may be equipped with a separate drive motor which will rotate the bar for milling. On this type of bar a grinding wheel may be mounted for fine finishing. The pentagon turret B' provides mounting for a series of tools for a sequence of boring and facing operations, the turret being indexed about its axis for each cut. This slide may be fed along the cross rail or down into the work.

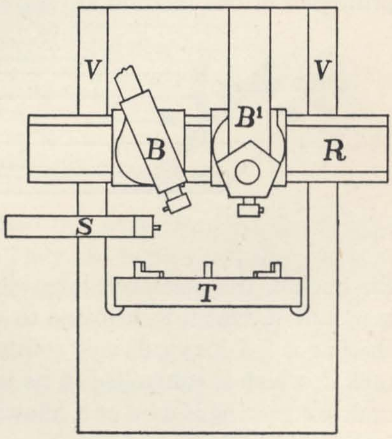


FIG. 71.

184. Cylindrical Grinder.—Surfaces are frequently finished by grinding because a fine finish can be obtained almost as rapidly as by

turning, and with a greater degree of accuracy. The cradle surfaces on the 3-in. M3 gun tube and the tapered surface of its liner are finished by grinding. Many shrinkage surfaces are also finished on the cylindrical grinder. The machine used is a modified commercial type similar to that used for finishing paper mill or printing press rolls. The work is mounted on centers on a carriage which is traversed along the bed. The grinding wheel is mounted in a housing at the back of the machine. Size is determined by feeding the grinding wheel toward the work.

185. Rifling Machine.—For rifling, a special machine is used, similar to the gun lathe but without headstock or turning carriage. The work is mounted in steady rests and does not rotate. The bar is fed longitudinally, as in the gun lathe, using a motor at the tailstock end of the machine. Twist of the rifling is controlled by two methods. The basic principles of one method are shown in Fig. 72. A bed O is attached at

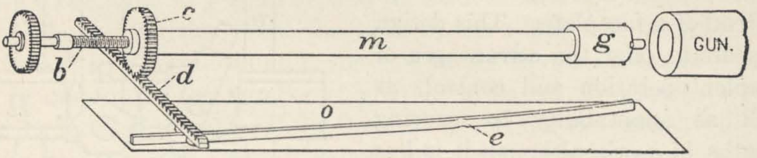


FIG. 72.

the back of the machine alongside the boring bench. Upon it a rail, e, is mounted, which is adjusted to the developed form of the rifling. As the bar is fed forward, it is rotated by means of gearing c turned by a rack d, which is controlled in its travel by a shoe sliding on the rail. If multiple gearing is used at c, allowance for the gear ratio must be made in setting the rail.

In the other method, a groove of proper twist is cut in the bar m, in which case the gearing, rack, and track are not required. A key in the forward bar support rides in the groove and turns the bar as it is fed along the bed. The grooved bar method is simpler and more positive, although the initial cost is greater. Torque of the bar is reduced to a minimum since twist is controlled near the work. Such accidents as movement of the track, breakage of the gearing or shoe, or improper setting of the track, which might damage the work, are eliminated.

186. Special Tools.—The *packed bit,* which is used for machining long bores of comparatively small diameter, is designed to hold the cutting tools in proper alignment and to guide them so as to insure a smooth, straight hole. The body A (Fig. 73) is usually of steel but on larger-sized tools may be of cast iron. It contains a tapered shank c which is accurately fitted and keyed to the bar of the boring lathe. For rough

or step boring, the cutters *b* are sharpened on the corners and the radial edges so as to give a small, tightly curled chip. For finishing, the cutters are slightly tapered toward the front of the tool and are sharpened on the outer edge, parallel to the axis of the bore, so as to give a thin, broad, continuous chip. The diameter to be bored is accurately set on the tool and is fixed for each setting. The piece being bored is rotated, and the tool is fed forward through the bore.

In order to provide support for the cutters and the end of the boring bar, blocks *D* of hard maple impregnated with oil are securely bolted to the body of the tool. The tool is equipped with oil pipes which lead cutting coolant under pressure to the cutting faces of the tools to keep them cool, and to flush out the chips ahead of the cut. Chips adhering to the cutting edges, or imbedded in the wood, will score the work.

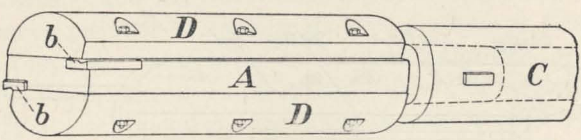


FIG. 73.—Packed Bit.

After each use, the woods are packed out with thin sheets of wood veneer between them and the body. They are turned to a size slightly larger than the bore just prior to each use. They must be concentric with the path of the cutting tools to prevent eccentric cutting. If they fit too tightly in the bore, the tool will run hot or the woods will wear rapidly. If the fit is too loose, the bit will tend to float and irregular cutting or vibration and chatter will result.

A counterbore must be cut in the starting end of the work to enable the woods to seat properly before the cutting edges make contact. If the bit is to start in a previously finished larger zone (as in step boring), strips are tacked to the woods with copper nails so that the tool will be accurately centered. As the cut progresses, these strips are sheared off against the shoulder left in the work or the tool may be withdrawn and the strips removed.

The *taper reamer* is similar to the packed bit except that the cutting tools extend the full length of the body and are sharpened throughout their length (Fig. 74). When used at a considerable depth, a brass pilot ring is provided at the forward end, and a similar brass collar may be used on the boring bar in rear, to center and support the tool. Powder chamber reamers conform to the contour of the finished chamber, combining all the required tapers in one tool. The pilot ring ahead fits the finished bore of the gun.

The *rifling head* consists of a body with a shank for attachment to the machine and a sleeve which conforms closely to the finished bore of the gun. Guide grooves are provided in the forward end of the body for the support and accurate spacing of the cutters. Any number of cutters may be used if they can be properly supported and operated; a tapered plug inside the body of the head holds the end of each cutter and provides the means for their radial adjustment outward for each cut, and retraction inward when the bar is withdrawn for a new cut. When one set of grooves is completely finished, the bar of the machine is rotated for the succeeding grooves. Rifling cutter equipment usually contains a break-down, a parting, and a finishing set. The break-down cutter starts the groove and bevels the corners of the lands to prevent burrs as the cut is deepened. The parting cutter carries a narrow groove to full depth,

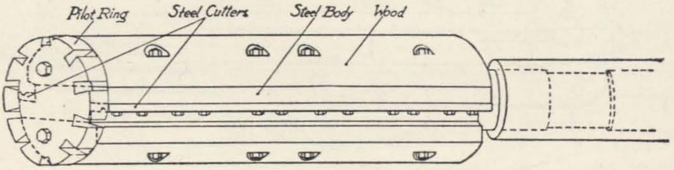


FIG. 74.—Taper Reamer.

and the finishing cutter widens it to form. Cutters must always be assembled in the head in the pockets to which they have been fitted. Each set must track the preceding set accurately. On 75-mm. and 3-in. guns, the finishing set, only, is generally used. Cutters must be able to cut the entire length of the bore without losing sharpness or varying the depth of cut, and all cutters must perform equally.

187. Assembling.—A modern major caliber built-up gun is composed of the following members, *liner* or inner tube, *tube, jacket, hoops,* and *locking rings* to hold abutting members together. Assembly throughout is by shrinkage. This construction is illustrated by the 16-in. Howitzer, Model of 1920, Fig. 55. The employment of a tapered shrunk-in liner permits subsequent re-lining of the gun when it reaches the end of its accuracy life through erosion of the bore. Just as the monobloc gun is replacing the built-up type in the smaller calibers, it is probable that a comparatively heavy monobloc tube will take the place of the tube and liner in larger calibers. Re-lining and re-tubing require arsenal operations because of the shrinkage involved.

The sequence of operations in assembling a typical built-up gun such as the 16-in. howitzer, or the 14-in. gun MII, is as follows: (1) shrinkage of jacket on tube, (2) successive shrinkage of the several layers of hoops

and rings over the assembled tube and jacket, and (3) the shrinkage of the assembly over the liner. A shrinkage sheet is prepared, showing the dimensions to which the inner surface of each outer member or assembly to be shrunk-on, and the outer surface of the inner member, are to be finish-machined so as to produce the required shrinkage pressure at the common surfaces. The heating of the outer member in each assembly operation, to produce the diametral expansion necessary to permit it to slip over the inner member, is performed in an electric furnace which permits accurate control of temperatures. The heats employed vary with the type of assembly, the size of the forgings, and the amount of shrinkage specified; a heating period of 20 or more hours may be required, and temperatures as high as 750° F. specified. The amount of expansion is checked by a reference gage when the cylinder is removed from the furnace, and just before assembly, to insure adequate clearance.

The inner member in each assembly operation is filled with cold water, and provision is made for its circulation through the bore, to prevent undue or uncontrolled absorption of heat, and expansion. It will be noted that each member except the outside hoop has one or more shoulders on its outer surface which must rest against corresponding shoulders on the inner surface of the next outer member, to prevent relative movement under the stresses incident to firing. Each outer member or assembly, when heated, expands both axially and radially and, as it cools and contracts, heat is transferred to the inner member causing its axial and radial expansion. The rate and manner of cooling, and of transfer of heat to the inner member, must be so arranged and controlled that the first contact of the two surfaces will be at the desired point, and that progressive contact shall be established in such a manner that each member will come to rest in its correct position, with a tight shoulder-to-shoulder bearing, and without any residual longitudinal stresses in the system. The following is a summary of the shrinkage operations in a typical gun such as the 16-in. howitzer, Fig. 55.

The tube (*B* tube), filled with water, is placed in the shrinkage pit, breech end down, and supported in a vertical position. The expanded heated jacket is lowered over the tube until seated upon its shoulder. Cooling is effected by the use of encircling water sprays directed on the point where the first shrinkage gripping is desired, and then gradually moved upward. After the assembly has cooled to shop temperature it is removed from the shrinkage pit, the correct shrinkage verified by measurements, and the exterior surface finish-machined for the next assembly operation. The successive preparation of the various hoops and rings, and their assembly, follows the same procedure outlined for the jacket and tube. The bore of the assembled gun is now finish bored

and taper reamed to receive the liner. In the discussion thus far, the heated outer member in each instance has been lowered over the muzzle end of the tube or assembly. In other methods of assembling, the heated jacket is placed in the shrinkage pit, breech end up, and the tube lowered into it. In certain older designs, for example the 12-in. Gun, Model of 1888, the shoulder on the tube was so constructed that the jacket had to be lowered over the breech end of the tube.

The procedure in shrinking the liner in the gun is as follows. The assembled gun is supported breech end up in the furnace and heated until the specified expansion is attained. The liner, sealed by plugs at both ends and filled with water, is then lowered to its proper seat upon the shoulder in the gun. Water connections are then made and cool water enters by means of a pipe through the breech plug extending downward close to the muzzle. A drain pipe also extends through the liner, fitted with a series of outlet valves, the top one a few inches above the shoulder and the others spaced at intervals of two or three feet towards the muzzle. These valves can be operated from outside the furnace, and the water level in the liner will drop to that of the lowest opened valve.

When the liner is seated on the shoulder, the top valve is opened and the water level falls to within a few inches of the shoulder. This permits rapid heat transfer from the breech end of the gun to the corresponding portion of the liner, which expands radially and axially and gradually establishes contact along the surface above the water level. In accordance with a predetermined time schedule, the other valves are opened progressively and the operation continued until the entire surface of the tube is in contact with the surrounding member. The ideal shrink would require a continuous lowering of the water level instead of in successive steps of several feet each.

The top valve is held slightly above the shoulder on the theory that the shrinkage above will hold the liner in place and that as the outer member cools it will contract axially against the shoulder. In the smaller guns, where the weight of the liner itself is not sufficient to hold it on its seat at the shoulder during shrinkage, a hydraulic jack bearing against the breech end of the liner is employed.

When the shrinkage operation is complete, the assembled gun is allowed to cool to shop temperature, which may require a week or more, and is then removed from the furnace and transferred to the machine shop for the final operations. These include finish turning of the exterior to final dimensions, milling of spline or keyway on exterior when specified by the design, finish boring of liner, chambering, rifling, and necessary machining of breech to receive the breech mechanism.

In the re-lining of a gun, the worn liner must be removed and a new one inserted. To remove the liner, the gun is heated in the electric furnace and, when the desired expansion is obtained, the bore is rapidly chilled and contracted by the use of circulating cold water. The worn liner can then be lifted out by the crane or forced out by use of a hydraulic jack at the muzzle, if necessary. The assembly of the new liner follows the procedure previously described.

188. Measurements.—In order that the gun may be assembled with the required shrinkages, the surfaces of the various cylinders composing the gun must be accurately turned and bored to the prescribed dimensions. The dimensions of all parts of the gun must be in accord with the design. The tolerance, or allowed variation from prescribed dimensions is, in general, 0.001 in. for the diameter of the shrinkage surface.

Accurate measurements of the various dimensions of every part of a gun are therefore essential. Interior measurements are generally taken with rods or points. Exterior sizes are obtained with micrometers, calipers, and vernier calipers. Commercial instruments are used whenever it is possible to adapt them to gun manufacturing processes.

189. Micrometers and Calipers.—Commercial micrometers are used for the measurement of outside diameters up to 24 in. Larger gun forgings require a specially constructed micrometer caliper.

The caliper has a strong pressed aluminum frame, sufficiently rigid to prevent change of form and light enough to handle and measure efficiently. It has two measuring or contact points. Point *a* slides and may be adjusted and clamped for the range in inches. Point *b* has a revolving micrometer head for fine adjustment. As for interior measurements, one end of the caliper, point *a*, is held firmly against the work while *b* is alternately adjusted and moved in two planes until the proper contact is attained (Fig. 75).

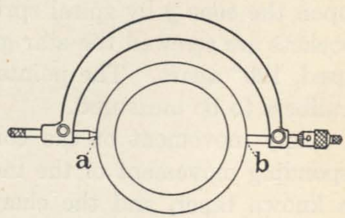


Fig. 75.

190. Boresearchers.—The interior or bore of each gun or forging when finished to size is examined for flaws or defects. A device called a boroscope, or bore telescope, is used for diameters up to 6 in. This gives the observer a constant magnified and illuminated view of the bore surface over a maximum distance of 20 ft.; longer guns or forgings are searched from each end. Defects, if found, can be further magnified and photographed. Major caliber guns and forgings are searched with a plain illuminated mirror fastened to a rod. The reflection of the bore

which lies above the mirror is magnified and carried to the observer by a separate focusing unit known as a tripod telescope.

191. The Star Gage.—For long tubes, all parts of which are not readily accessible, some means must be adopted of making the measurements at a distance from the operator. The instrument used for this purpose is called a star gage.

Its general features are shown in Fig. 76. The long hollow rod or staff *a* carries at its forward end the head *b*. Embracing the rear end of the staff is the handle *c* to which is attached the square steel rod *f*. The handle has a sliding motion or screw motion on the end of the staff, and any movement of the handle is communicated through the rod *f* to the cone *g* in which the square rod terminates at its forward end.

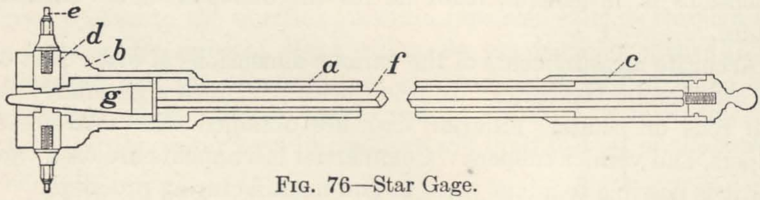


FIG. 76—Star Gage.

The head *b* has three or more sockets *d*, which are pressed inward upon the cone *g* by spiral springs not shown in the figure. Into these sockets are screwed the star gage points *e*. Three points are generally used, 120° apart. The points are of different lengths for the different calibers to be measured.

Any movement of the cone forward or backward causes a corresponding movement of the measuring points out or in. The cone has a known taper, and the change in its diameter under the measuring points due to any movement of the handle is marked on a scale at the handle end of the staff. The handle carries a vernier by means of which the scale may be read to a thousandth of an inch. The reading of the scale is the change in length of the diameter that is measured by the points when the handle is at the zero mark.

The staff *a* and rod *f* are made in sections, usually 50 in. long, so that the gage may be given a length convenient for the measurement of any length of bore.

The star gage is set for any measurement by means of a standard ring of the proper diameter. The standard rings are of steel, hardened and very carefully ground to the given diameter. If it is desired to measure a 10-in. bore, for instance, measuring points of the proper length are inserted in the sockets *d* of the star gage. The 10-in. ring is held surrounding the points, and the handle *c* of the star gage is pushed

in until the points touch the inner surface of the ring. The handle is then adjusted until the reading of the scale is zero. The instrument is now ready for use.

The gun or forging whose bore is to be measured is supported so that its axis is horizontal. The star gage is also carefully supported in the axis of the bore prolonged, and in the bore when necessary. The distance of the measuring points from the face of the bore is read from a scale of inches marked on the staff. At each selected position of the gage the handle is pushed forward until the measuring points touch the surface of the bore. The difference between the diameter of the bore at this point and the standard diameter for which the gage is set is then read from the scale at the handle in thousandths of an inch.

CHAPTER VI

BREECH MECHANISMS

192. General Characteristics.—A breech mechanism is a mechanical device for closing the rear end of the chamber or bore of a gun after loading, and for firing the round of ammunition which has been inserted. The component parts of a modern breech mechanism include (1) the *breechblock,* (2) the *firing mechanism,* and (3) the *mechanism for the insertion and withdrawal or opening and closing of the breechblock.* Except when obturation is performed by a cartridge case, an obturating device must be provided. The operation of most modern breech mechanisms, particularly for medium and heavy artillery and for antiaircraft artillery will usually include one or more automatic features. The principal requirements of a satisfactory breech mechanism are:

a. Safety, which means that the parts must have ample strength to withstand the firing stresses; the gases must be prevented from escaping to the rear; the block must be securely locked to prevent opening when the gun is fired; the danger of premature discharge must be avoided; and the entire mechanism assembly must be securely attached to the gun in its jacket or breech ring.

b. Adaptability to Quantity Production.—It is most essential that adaptability to quantity production in emergency be considered one of the most important requirements of design.

c. Ease and rapidity of operation, necessary for rapid and continuous fire. The minimum of effort of loading, closing, and firing and the certainty of opening the block immediately after firing are of paramount importance.

d. Reliability and durability, necessary to meet the conditions of hard service usage. Design of the mechanism calls for protection for the more fragile parts and for wear-resisting characteristics for moving parts and wherever wear occurs.

e. Ease of repair, necessitating simplicity of design and accessibility of all component parts. Interchangeability of sub-assemblies and of individual parts should be easily permitted at the gun position.

. The breechblock is usually supported in the jacket of the gun or in a breech ring affixed to the tube or the jacket. The seat in the jacket or

breech ring being of greater diameter than could be provided in the tube, the bearing surface of the screw threads on the block is increased and the length of the block may be diminished. With built-up or wire-wrapped guns it will be noted that, by supporting the breechblock in the jacket, the longitudinal firing stresses are not taken directly by the tube.

193. Types of Breech Mechanisms.—There are three general types of breech mechanisms in use on the guns of our service. These are (1) *slotted-screw* type, (2) the *eccentric-screw* type, and (3) the *sliding-wedge* type. On designs of the sliding-wedge type, the wedge may be withdrawn from its seat either by a horizontal or by a vertical direction of motion. Two other distinct types which are less adaptable to artillery, but are commonly used on automatic weapons and small arms, are the *combined sliding and rotary type* and the *sliding-bolt type.*

The *slotted-screw* type of breechblock is mounted on a block carrier which is hinged to the breech section of the gun and is carried thereon when not actually inserted in the breech. This carrier may be given either a horizontal or vertical movement in order to permit the block to clear the breech for loading. When the block is out of the breech it must be securely fastened to the carrier, and rotation must be prevented to insure proper engagement of the threads when closure is desired. The breechblock is provided with screw threads on its outer surface which engage in corresponding threads in the breech of the gun. The pitch of the threads is such that, under the force of the powder pressure, friction will prevent the block from rotating and opening the breech due to the component of the force along the screw threads. In order to facilitate insertion and withdrawal of the block, the threads on block and breech are interrupted. The threaded surface of the block is divided lengthwise into an even number of sectors and the threads of the alternate sectors are cut away. Similarly, the threads of the breech are cut away from those sectors opposite the threaded sectors of the block. In closing the breech the threaded sections of the block are brought opposite to the blank sections of the breech recess and the block may be rapidly inserted nearly to its seat in the gun. When the block is then turned through a comparatively small arc, say 1/8, 1/12, or 1/16 of a circle, depending upon the number of sectors into which the block is divided, the threads on the block are fully engaged with those in the breech recess and the breech closed. The slotted-screw type may be used on all types of cannon but does not readily lend itself to automatic features of operation. Its principal advantages are strength, reduction of weight in the breech section, uniform distribution of the longitudinal stress produced by the powder pressure, and adaptability to approved

methods of securing obturation with separate-loaded ammunition. In addition to the plain interrupted screw described, the slotted-screw type includes also the stepped-thread and the conical or ogival-faced blocks. The firing mechanisms may be incorporated as a permanent sub-assembly to the block or may be separately inserted in the block as a complete unit assembly.

The *eccentric-screw* or "Nordenfelt" type of block is cylindrical in form and is threaded on its outer surface to screw into the breech recess. The block is made much larger than the chamber of the gun and the axis of the block is eccentric to the axis of the bore. The breech is opened by rotating the block slightly less than half a revolution about its axis so that a U-shaped opening or port at one side of the center is brought into axial alignment with the bore. The block remains in the breech recess during the operation of opening or closing the breech. The mechanism, being all enclosed, is not liable to damage and permits rapid operation. It is too heavy for large guns. This type of block is exemplified in the breech mechanism of the 75-mm. Gun, Model 1897 (French), and is fully described in the chapter on artillery.

The *sliding-wedge* type of breech mechanism employs a rectangular wedge-shaped block, securely seated in a slot cut in the breech of the gun perpendicular to the bore, and sliding in this slot under the action of an operating lever, to open and close the breech. The motion may be either vertical or horizontal according to the design of the block and the direction of the slot; where vertical operation is provided the mechanism is classified as the *drop-block* type. The sliding-wedge system is readily adaptable to automatic features of operation. Its advantages include simplicity of construction and rapidity of action. It is used on all antiaircraft cannon in our service and generally in all new weapons using fixed ammunition. The system is not as well adapted for use with separate loading ammunition because of difficulties of effecting proper obturation when the propelling charge is not contained in a metal cartridge case. Also, its use necessitates employment of relatively heavy breech sections to provide the strength required to withstand the firing stresses.

Variations of these three general types of breechblocks will be noted in the following descriptions of the breech mechanisms of some of the guns in service.

194. The Slotted-screw Breech Mechanism for Heavy Guns.— An example of the slotted-screw breech mechanism as used in the heavier guns is shown in Figs. 77 to 79, which represent the breech mechanism of the 12-in. gun. The breechblock has six threaded and six slotted sectors. When the breech is closed the threads on the block

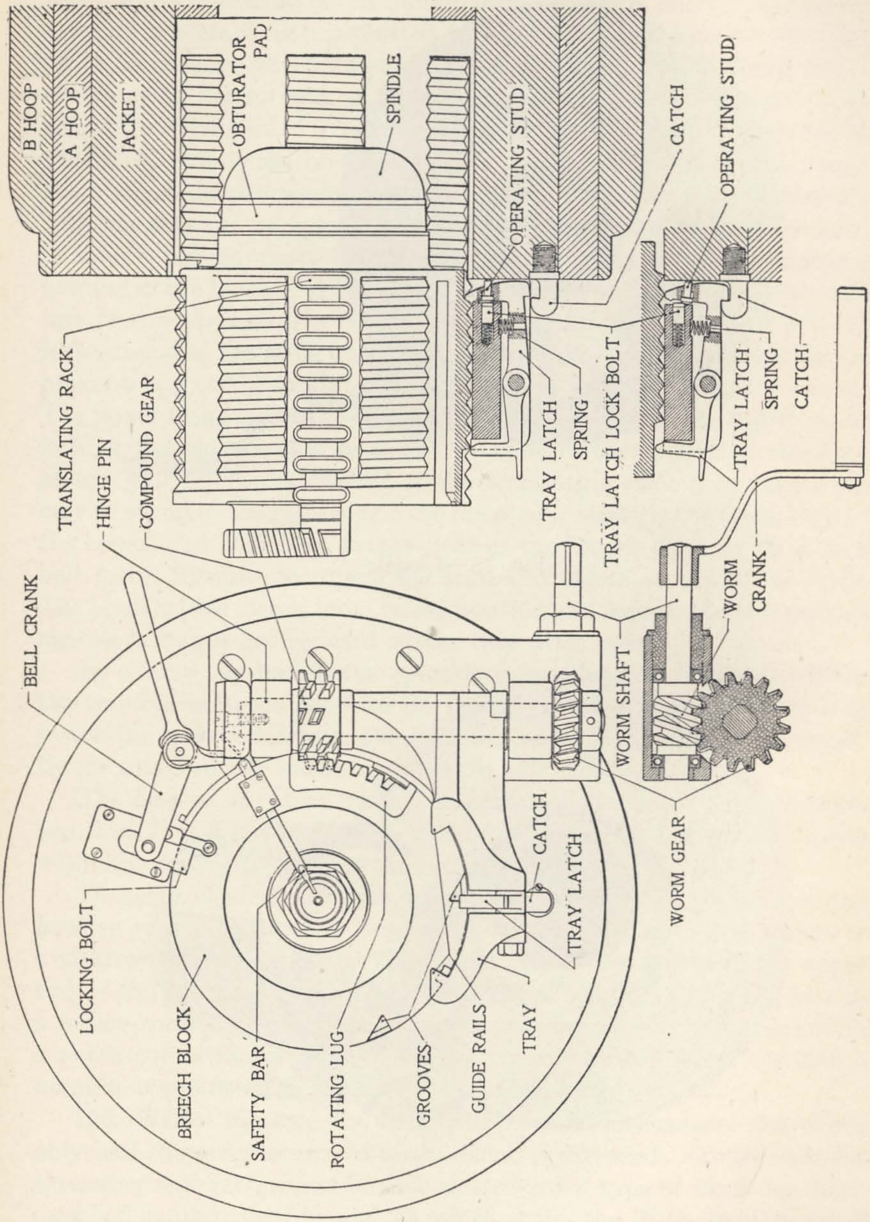


FIG. 77.—Breech Mechanism, Old Type, for Heavy Guns.

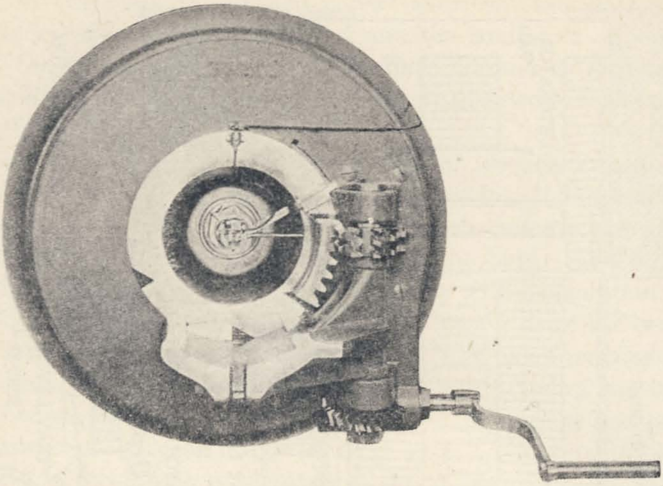


FIG. 78.—Closed.

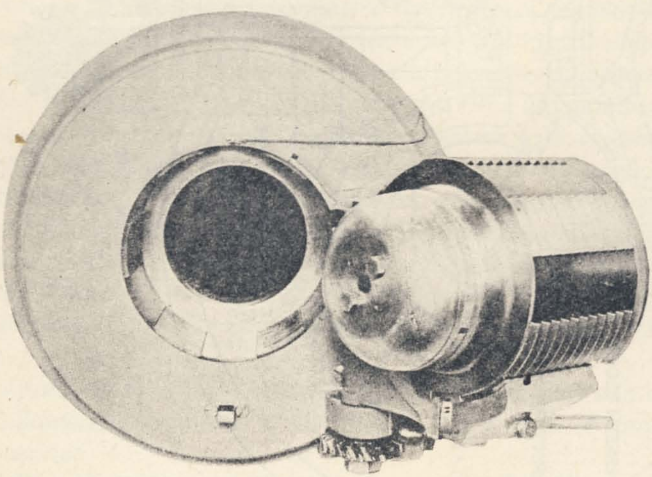


FIG. 79.—Open.

Breech Mechanism for Heavy Guns.

engage with the threads in the breech recess. The breech is opened by turning the operating crank mounted on the worm shaft. The movement of the crank is transmitted through the worm gear to the hinge pin, and through the compound gear near the top of the hinge pin to the rotating lug formed on the rear of the block. The block is thus rotated one-twelfth of a turn, and its threaded sectors then lie in the slotted sectors of the breech. Further movement of the crank causes the teeth of the compound gear to engage in the teeth of the translating rack cut in a slotted sector of the block. The block is thereby caused to slide to the rear on to the tray, the guide rails of the tray engaging in grooves in the block. When the block is sufficiently withdrawn the bottom of the block depresses the rear end of the tray latch and lifts the forward end of the latch out of the catch, where it has been held by the pressure of a coiled spring. The tray is now unlocked from the breech. The upper front toe of the latch engages in a groove in the breechblock, locking the block and tray together. The further action of the compound gear on the last teeth of the translating rack then causes the tray to swing to the right about the hinge pin, carrying the block clear of the breech. As the tray swings clear of the breech the tray latch lock bolt forces forward the operating stud and enters a seat in the latch. The latch is thus locked in its raised position and secures the breechblock against being pushed forward off the tray when open.

In closing the breech the operations are reversed in order. When the tray comes in contact with the face of the breech the operating stud forces the lock bolt from its seat in the latch. The latch is depressed by the coiled spring and thus unlocks the block from the tray.

The two plugs shown in the obturator head of the breech mechanism, Fig. 79, are in the seats provided for the insertion of pressure gages when it is desired to measure the pressure in the gun.

To insure against the opening of the block by the pressure of the powder gases, the block is locked in position when closed by means of a locking device attached to the breech face of the gun near the upper end of the hinge pin. The longer arm of a bell crank is connected to a spring-controlled locking bolt, the lower end of which is engaged in a notch cut in the block. The short arm of the bell crank fits into a notch in a cap fitted to the upper end of the hinge pin.

195. Welin Blocks.—In the slotted-screw mechanism described, only half the outside surface of the block is threaded. To provide for threading a larger proportion, the slotted-screw type of block has been modified as illustrated in Fig. 80, which shows the *Welin stepped-thread block.* In this block the threaded sectors are built in two or three steps, the blank sectors being of less diameter than any threaded sector. The

breech recess is also threaded in steps to correspond, here the blank sectors being of larger diameter than any threaded sector. To unlock the breech, the block is turned so that its threaded sectors are rotated into the sectors of larger radius in the breech, thus permitting the block to be withdrawn.

By this means the threaded area may cover two-thirds, three-fourths, or even a larger portion of the surface of the block. This gives two advantages over the cylindrical block with alternate threaded sectors. A large increase in threaded area is secured which permits

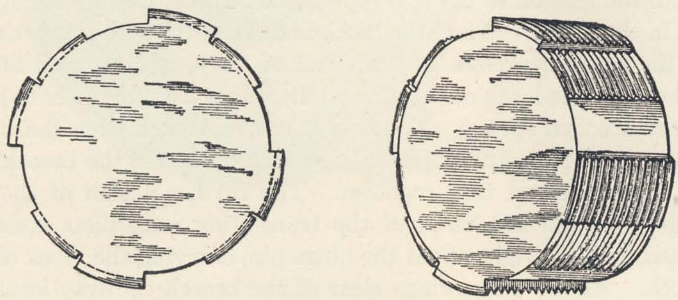


FIG. 80.—Welin Stepped-thread Breechblock.

the use of a smaller block. The amount of rotation required to lock and unlock the breech is also diminished.

The Welin block is illustrated in Fig. 81, which shows the breech mechanism for the 14-in. Gun, Models of 1907 and 1910. This mechanism is practically the same as that described in Section 194 except for the breechblock and the type of compound gear used to translate and rotate the block.

196. The Bofors Breech Mechanism.—Another method of obtaining a larger threaded area, thus permitting the block to be shortened, is illustrated by the *Bofors breech mechanism* shown in Fig. 82. The block and the breech recess are very wide at the rear, thus increasing the bearing surface. The block is ogival in shape and has six threaded and six slotted sectors. With the ogival shape a very small retraction to the rear is necessary before the block may be swung open. The block is supported, when the breech is opened, by the block carrier provided with a central tube which embraces a spindle formed in the rear of the block. The block carrier is hinged to the right side of the breech by the hinge pin and two hinge lugs. The loading tray shown in the figure is to protect the threads of the breech from injury. When the block enters the breech recess and is rotated, the tray is pushed aside by the threads on the block until it covers the slotted sectors.

The Bofors mechanism is used in some models of 6-in. guns in our service.

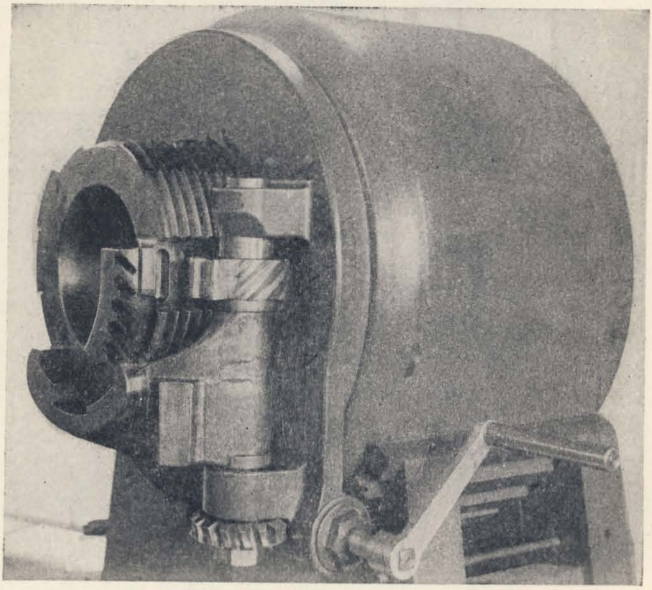


FIG. 81.—Breech Mechanism, Old Type, for 14-in. Guns.

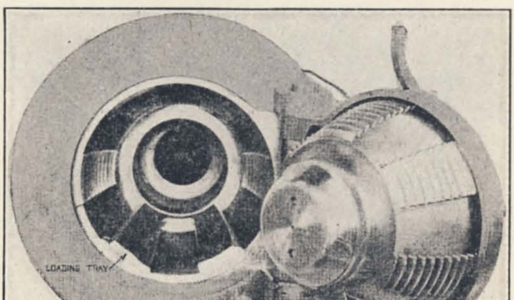


FIG. 82.—Bofors Rapid Fire Breech Mechanism.

197. Breech Mechanism, Mk. II, for 14-in. Guns.—An example of the type of breech mechanism used with 14-in. guns of current design is illustrated in Figs. 83 to 86 and is designated as the 14-in. Breech Mechanism, Mk. II.

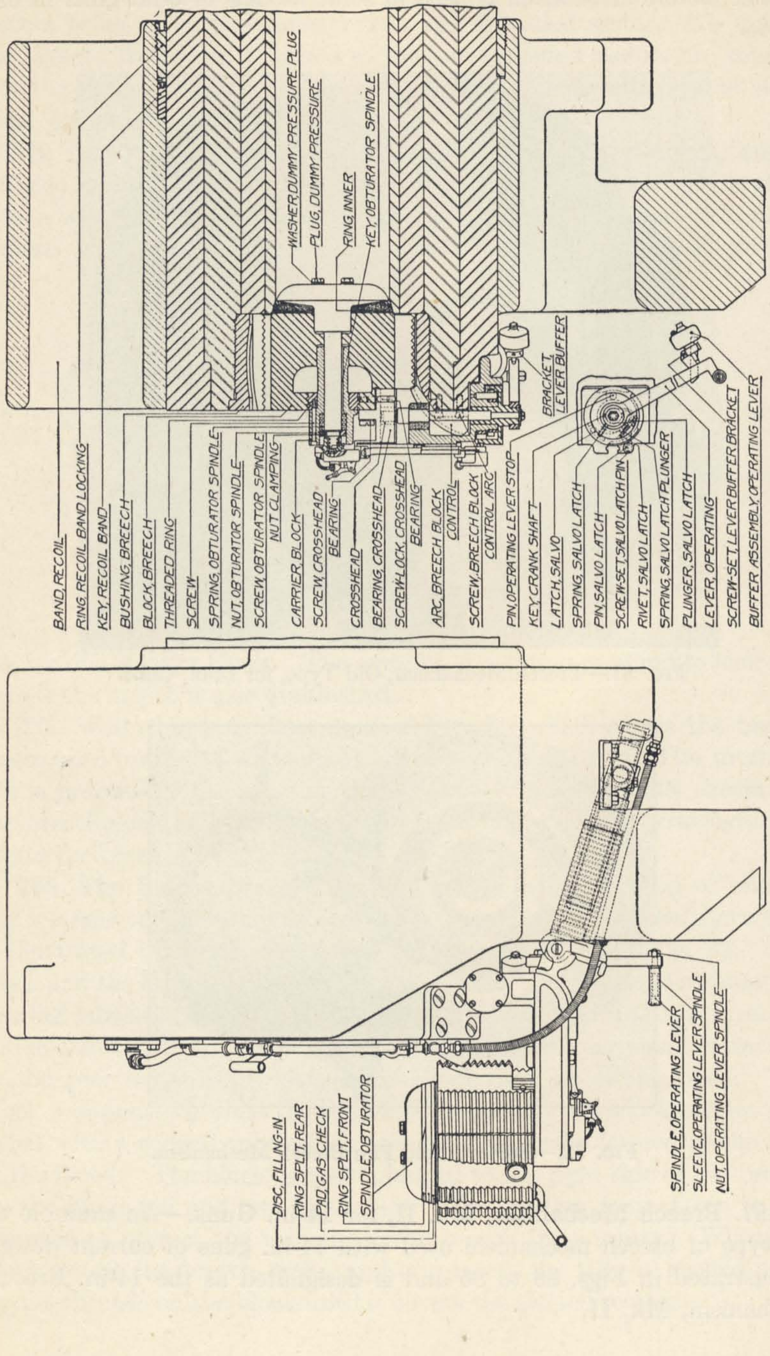


FIG. 83.—14-in. Breech Mechanism, Mk. II. Right Side and Vertical Section.

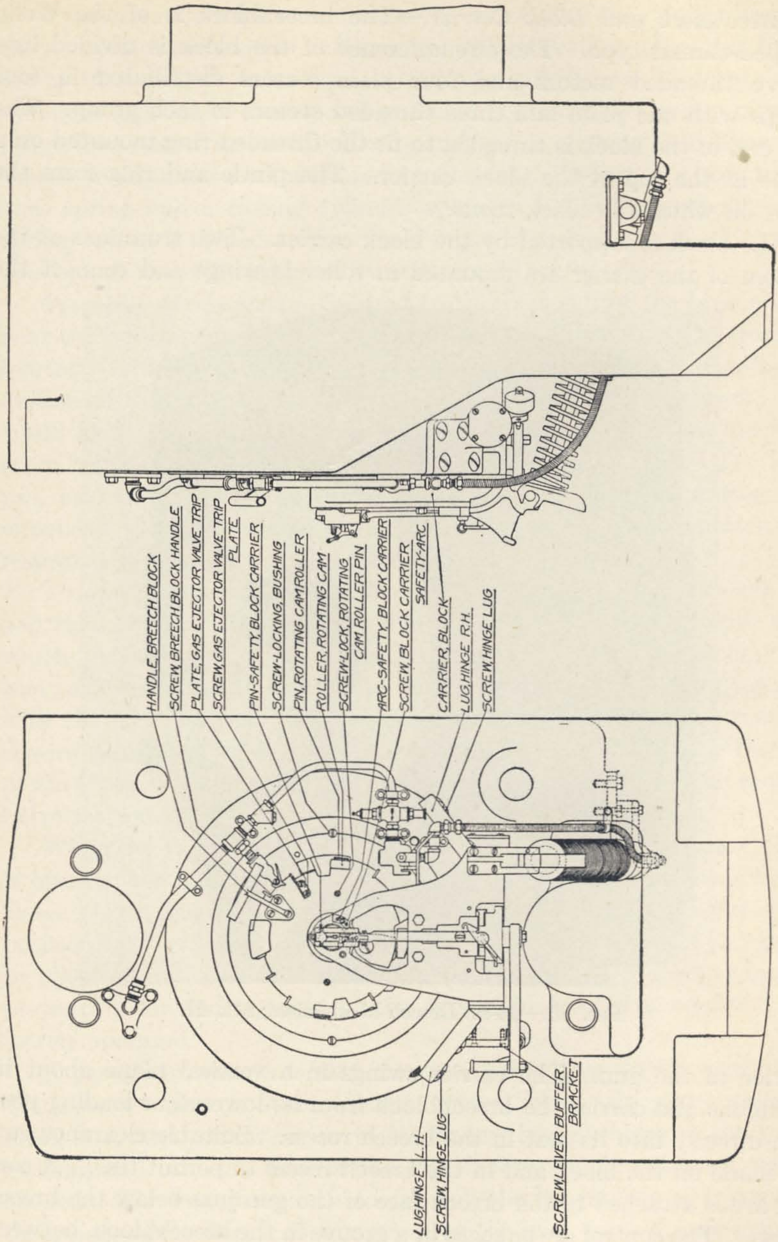


FIG. 84.—14-in. Breech Mechanism, Mk. II. End and Right Side.

Breechblock and Block Carrier.—The breechblock is of the Welin stepped-thread type. The circumference of the block is divided into twelve threaded sectors and four plain sectors distributed in four groups with one plain and three threaded sectors in each group. The rear end of the block is threaded to fit the threaded ring mounted on a pintle at the top of the block carrier. The pintle and ring form the pivot on which the block turns.

The block is supported by the block carrier. Two trunnions at the bottom of the carrier are mounted in roller bearings and connect the

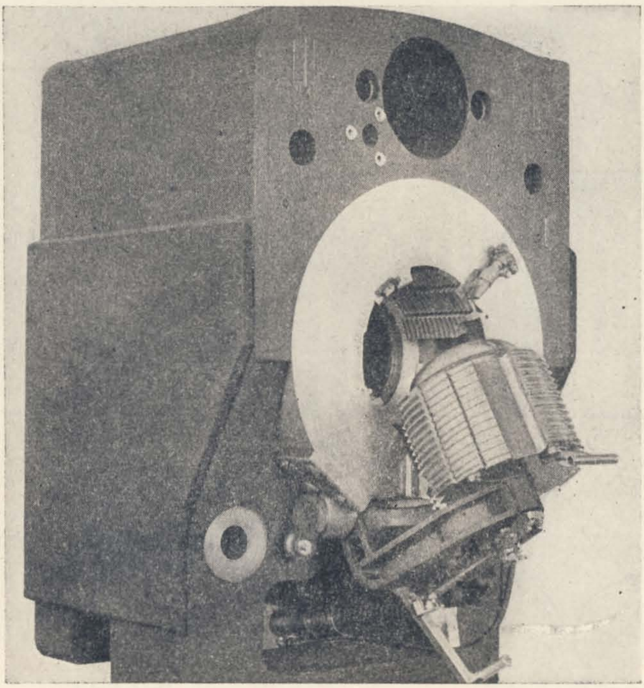


FIG. 85.—14-in. Breech Mechanism, Mk. II.

carrier to the gun. The carrier swings in a vertical plane about its trunnions and carries the breechblock from its lowered or loading position directly into its seat in the breech recess. Suitable clearance cuts are made on the block and in the breech recess to permit this. A control arc is attached to the breech face of the gun just below the breech recess. The control arc engages in a groove in the breechblock, between the two bottom threaded sectors, and prevents the block from rotating out of alignment with the sectors in the breech recess while it is in the open position.

Two cam rollers are mounted on the rear end of the block diametrically opposite each other. When the block swings into the breech recess these rollers enter cam surfaces in the breech bushing. This reduces the shock of closing and assists in changing the motion of translation into one of rotation. The operations of opening and closing the breech mechanism are facilitated by the introduction of a counterbalance spring and a closing cylinder operated by compressed air. The spring rod is attached to the lower right corner of the block carrier. The breech normally is closed by compressed air.

Operating Mechanism.—Secured to the rear end of the breechblock, near the bottom edge and in a pocket which confines it, is the *crosshead bearing.* This bearing receives the crosshead, which transmits the motion of the *operating lever* and *crank shaft* to the breechblock. The crank shaft is mounted vertically in the block carrier, the operating lever being attached to the lower end of the crank shaft. The *crank pin,* on the crank at the upper end of the crank shaft, engages the crosshead which is capable of both a sliding and a rotary motion with respect to its bearing and the crank pin.

To open the mechanism, the operating lever is swung to the rear and right, by hand, as far as it will go. This rotates the crank shaft, which, by means of the crosshead, rotates and unlocks the block. The *cam rollers* and *roller paths* guide the block to the point of engagement with the control arc. The mechanism is then swung to the rear and downward by means of the breechblock handle attached to the rear face of the block. When open, the mechanism is supported by the counterbalance spring, which also serves as a buffer.

When the valve which admits compressed air to the closing cylinder is opened, the air pressure on the piston at the end of the spring rod closes the mechanism. The operating lever is locked in the closed position by the *salvo latch,* and is unlocked by the recoil of the gun or by releasing the salvo latch by hand. The salvo latch is a safety feature, preventing hurried opening of the breech in case of a misfire. It is inertia operated.

A gas-ejector system is also incorporated in this breech mechanism. The ejector valve is automatically opened by a trip plate when the block is rotated, allowing air to be blown through holes in the breech bushing and into the bore of the gun before the breechblock can be opened. The compressed air for closing the mechanism is taken from the gas-ejector system. Before reaching the inlet valve the air is passed through a reducing valve which maintains a constant pressure.

The breech mechanism for the 16-in., 50-caliber Guns, Model of 1919 MI, MII, and MIII, shown in Fig. 86, is similar in design to that

described above. It differs mainly in two details: (*a*) the operating lever operates in a vertical plane instead of swinging to the rear in a horizontal plane and then down; and (*b*) the mechanism has two counter-balance springs and two closing cylinders, instead of but one of each.

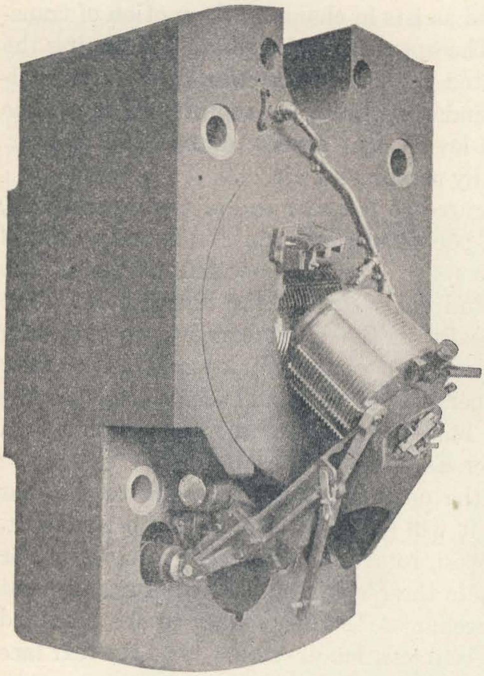


FIG. 86.—Breech Mechanism for 16-in. Gun, Model of 1919.

198. Obturation.—There must be provided at the breech of the gun some device that will prevent the powder gases from passing to the rear into the threads and other parts of the breech mechanism. If any passage is open to the gases they are forced through it with great velocity by the high pressure existing in the bore. Their velocity, together with their high temperature, gives to them great erosive power, and the threads and other parts of the breech mechanism subject to their action are eroded, channeled, and worn away to such an extent that the breech mechanism is soon ruined and the gun is rendered useless.

In guns that use fixed ammunition the obturation is performed by the cartridge case, which expands, under the pressure in the bore, to a tight fit against the walls of the gun. The breech mechanism of these guns contains, therefore, no obturator parts.

With guns using separate loading ammunition some device must be included in the breech mechanism to prevent the escape of the powder gases to the rear. For this purpose, the DeBange system of obturation is used exclusively in our service.

The DeBange Obturator.—This system is used with the breech mechanisms illustrated in Figs. 77 to 82. The details are shown in Fig. 87. The obturator consists of the steel mushroom head *h* with the spindle *s*, the pad *p*, the steel split rings *r*, and the steel filling-in disc *d*. The pad *p* is made of asbestos, tallow, and paraffin, forming a plastic

mixture that melts only at a high temperature. The ingredients are mixed and then pressed into shape under a hydraulic press and protected by a cover made of canvas or of asbestos-wire cloth. The split rings, Figs. 87 and 88, are hardened, and their outer surfaces are coned toward the front, so that their diameters when the rings are free are 0.01 in. larger than the diameters of the conical seat in the bore. The edges of the rings therefore always bear against the walls of the bore.

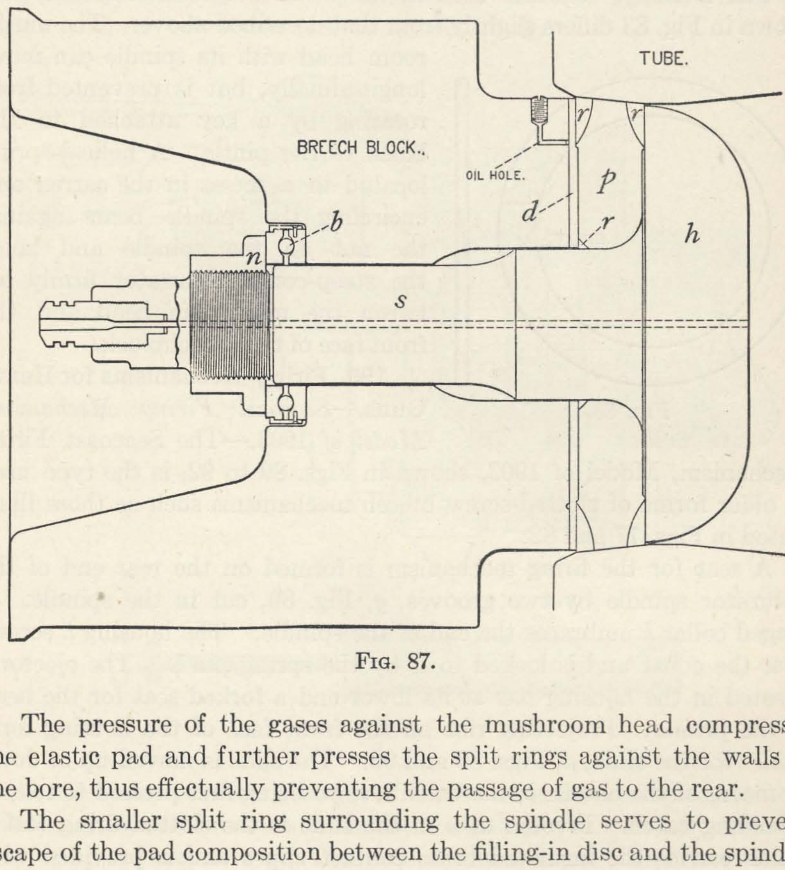


FIG. 87.

The pressure of the gases against the mushroom head compresses the elastic pad and further presses the split rings against the walls of the bore, thus effectually preventing the passage of gas to the rear.

The smaller split ring surrounding the spindle serves to prevent escape of the pad composition between the filling-in disc and the spindle. In the latest types of obturator the smaller rings are not split because solid rings have been found satisfactory for use next to the spindle.

The spindle *s* passes through a central hole in the breechblock. The obturator parts are held in place by the split nut *n* clamped on the spindle. The nut bears against a shoulder in the block through the ball bearing *b*. It will be seen that the breechblock may rotate independently of the obturator parts, so that in opening the breech the

rotation of the block is not affected by any sticking of the obturator to its seat in the gun. On retraction of the block the obturator is readily withdrawn from its conical seat.

A vent is drilled the full length of the obturator spindle to afford a passage for the flame from the primer to the powder charge in the gun. The two grooves at the rear end of the spindle serve for the attachment of the firing mechanism.

The *DeBange obturator* used in the 14-in. breech mechanism, and shown in Fig. 83 differs slightly from that described above. The mushroom head with its spindle can move longitudinally, but is prevented from rotating by a key attached to the block carrier pintle. A helical spring located in a recess in the carrier and encircling the spindle bears against the nut on the spindle and holds the steep-coned obturator firmly between the mushroom head and the front face of the breechblock.

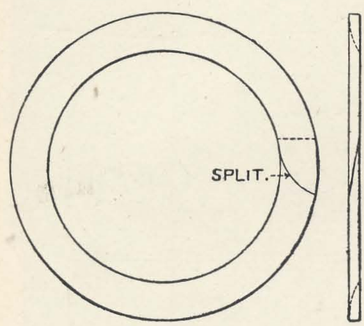


FIG. 88.

199. Firing Mechanisms for Heavy Guns.—*Seacoast Firing Mechanism, Model of* 1903.—The Seacoast Firing Mechanism, Model of 1903, shown in Figs. 89 to 92, is the type used on older forms of slotted-screw breech mechanisms such as those illustrated in Figs. 77 and 82.

A seat for the firing mechanism is formed on the rear end of the obturator spindle by two grooves, *g*, Fig. 89, cut in the spindle. A hinged collar *k* embraces the end of the spindle. The housing *h* screws over the collar and is locked to it by the spring pin *p*. The ejector *e* pivoted in the housing has at its lower end a forked seat for the head of the primer. Projecting ribs on the front face of the housing form guides for the slide, *d*, Figs. 89 and 90. The slide is moved up or down by means of the handle *b*, the catch lever *a* being first pressed to release a holding catch. Pivoted at *o* in the slide is the slotted firing leaf *l*, which carries the insulated brass contact clip *c* and is provided with an eye into which the hook of the lanyard engages.

The slide being at its uppermost position, the primer *r* is inserted in the vent in the obturator spindle, the head of the primer resting in its seat in the ejector. The slide is then pushed down. The firing leaf *l*, by means of the slot, embraces the insulated primer wire just in front of the button at its outer end. The two halves of the contact clip *c* spring apart and embrace the uninsulated button.

If the breech is closed, a pull on the lanyard rotates the firing leaf l about its axis o, drawing out the primer wire and firing the primer by friction; or the closing of the electric circuit, which enters the mechanism through the electric terminal n, will fire the primer electrically. The electric current passes through insulated parts to the contact wire inside the primer and thence through the body of the primer to the metal of the gun and to ground.

Firing by either of these methods cannot be accomplished unless the slide d is all the way down and the breech is fully closed.

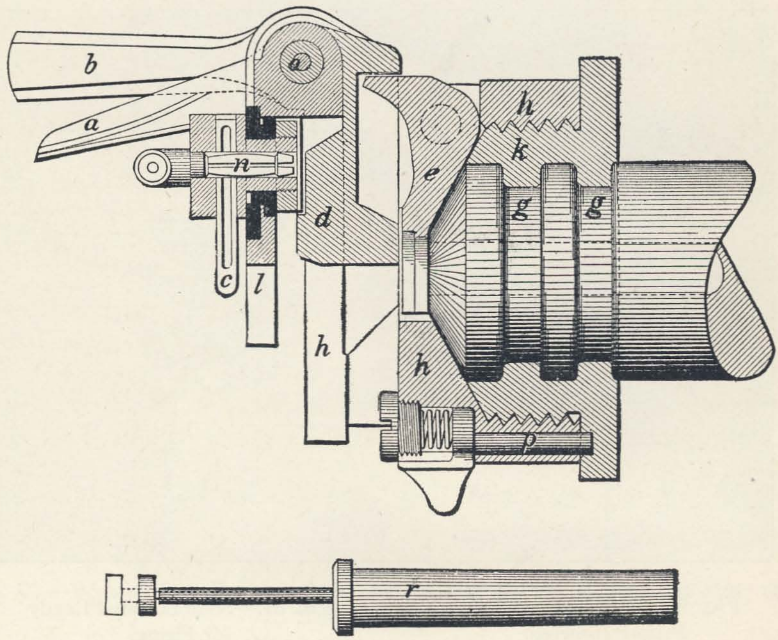


FIG. 89.

A safety lug on the right side of the housing engages in a groove in the firing leaf and prevents the latter being drawn to the rear before the slide is all the way down. The contact clip engages the primer button only in the last part of the downward movement of the slide.

The inner end of the safety bar, s, Fig. 90, also engages the firing leaf. The outer end of the safety bar embraces a stud projecting from the safety bar slide, i, Fig. 92, and the safety bar slide carries at its outer end a stud that engages in a groove cut in the gun. The groove is so shaped as to withdraw the safety bar only at the last part of the movement of the block in closing. At this moment also the parts of

the electric circuit breaker, fixed one to the block and the other to the gun, Fig. 92, come into contact.

It will be seen, therefore, that the primer cannot be fired until the breechblock is locked.

We have seen that the breechblock rotates independently of the obturator spindle. In order then that the firing mechanism may always be in an upright position when the breech is closed, a guide bar, *m*, Fig. 92, fixed at one end to the housing and at the other end to the block, causes the mechanism to rotate on the spindle with the block.

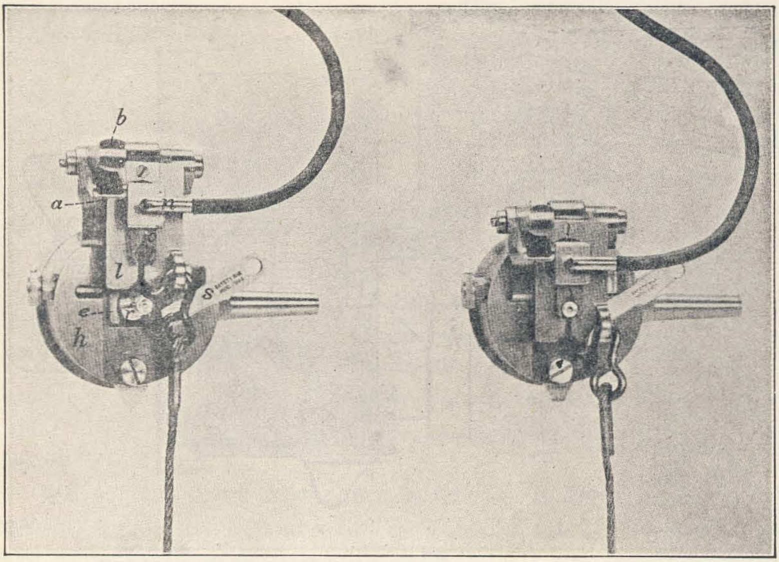


FIG. 90.—Slide Raised and Primer Inserted.

FIG. 91.—Slide Lowered Ready for Firing.

The fired primer is ejected by lifting the slide. The lug on the slide, *d*, Fig. 89, strikes the upper part of the ejector lever, giving to the lower end a sharp movement to the rear, which throws the primer clear of the piece.

Firing Lock, Mk. I.—The firing mechanism used on the 14-in. Breech Mechanism, Mk. II, is shown in Fig. 93. It is known as the Firing Lock, Mk. I, and is the type of firing mechanism used on the breech mechanisms of all guns now being constructed which use separate loading ammunition.

The assembled firing lock is attached to the rear end of the obturator spindle by pushing it over the end of the spindle and giving it one-fourth

of a turn to the locked position. Annular grooves on the rear of the spindle and in the firing-lock housing are divided longitudinally into two plain and two grooved sectors, which make possible this manner of assembly.

In the upper part of the firing-lock housing, which is attached to the spindle, is the primer-retaining catch with its operating spring. The extractor, a fork-shaped piece which straddles the head of the

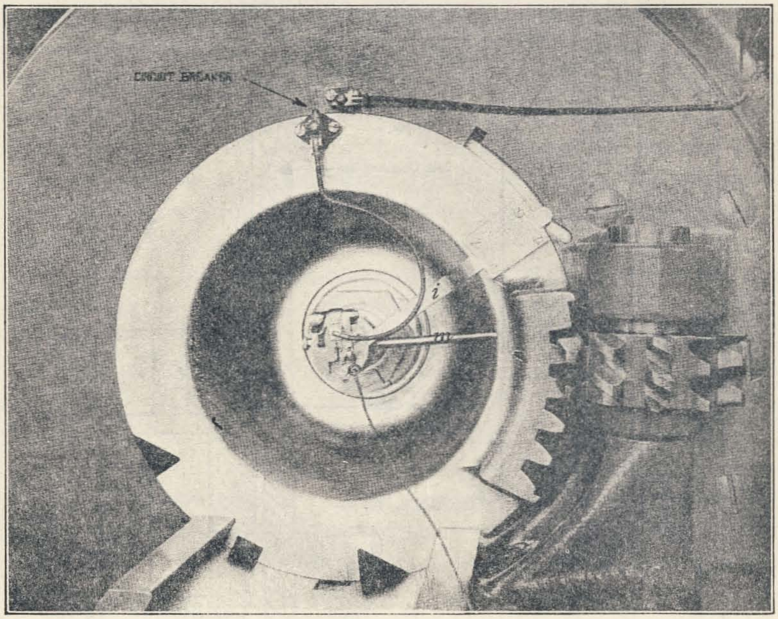


FIG. 92.—Breech Partially Unlocked. Safety Bar Forced in by Cam Slot, and Electric Circuit Broken.

Seacoast Firing Mechanism, Model of 1903.

primer, is also located in the firing-lock housing. The extractor is actuated by an extractor cam provided with a torsional spring.

The firing-lock slide moves vertically in grooves in the sides of the housing described above. The lower end of the slide contains an elongated slot to form a connection for the lock-operating bar. The lock-operating bar moves vertically in a T-slot in the rear face of the breechblock carrier. A plunger at the bottom of the operating bar moves in a helical groove on a cam attached to the lower end of the crank shaft, just above the operating lever.

The firing pin is mounted in insulated bushings in the top part of

the slide. A hardened faceplate is placed in the front face of the slide to take the thrust of the primer when fired. A projection on this faceplate bears against the extractor cam and actuates the extractor when the slide is lowered.

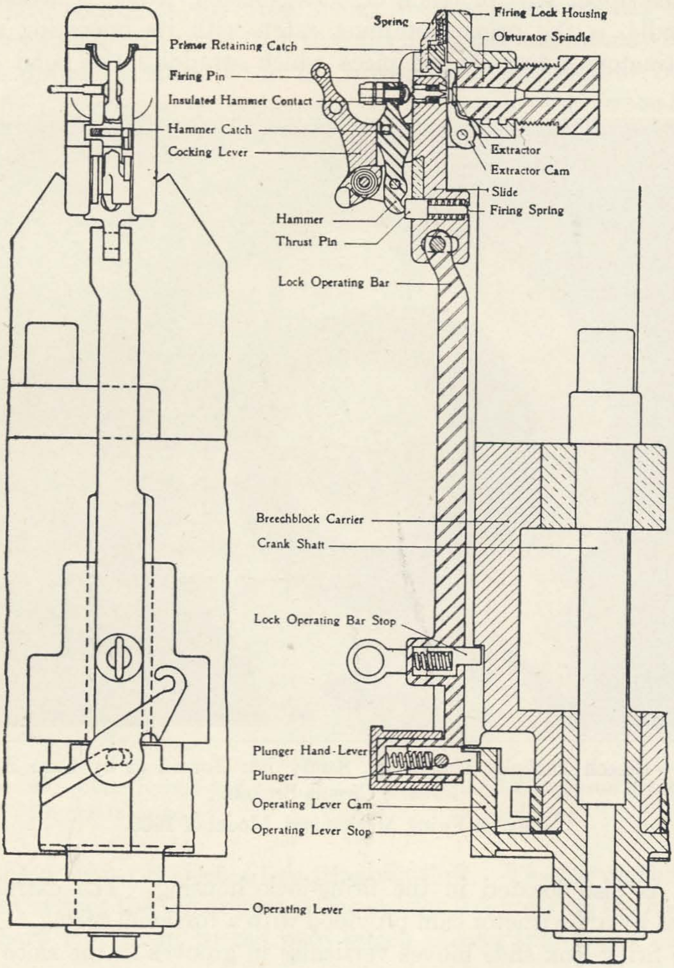


FIG. 93.—Firing Lock, Mk. I, and Operating Mechanism.

When the breech is opened, the operating lever cam withdraws the operating bar by means of the operating bar plunger, and thus the slide is lowered and the primer ejected. In case of a misfire the lock can be reprimed, without rotating the breechblock, by means of the hand lever at the bottom of the operating bar. Pulling down cn this

hand lever disengages the plunger from the operating lever cam. This permits the operating bar to drop downward, carrying the slide with it and thus operating the extractor. A new primer is then pushed into the chamber of the spindle until it passes the primer retaining catch, and the operating bar is raised until the plunger engages in the cam groove. The travel of the operating bar is limited by a stop attached to its lower end.

The hammer and the cocking lever are mounted on a bracket attached to the rear of the slide, their axes being parallel to each other and in the same horizontal plane. The hammer has fitted into its right side a spring catch which acts in conjunction with the cocking lever. The cocking lever is in rear of the hammer and is provided with a hole at the top for attaching the lanyard. A torsional spring about its axis tends to drive the cocking lever forward. When the cocking lever is drawn back for percussion firing, a latch on the lever engages with the catch on the hammer so that the hammer is also drawn back until their relative positions are such that the hammer catch slides off the latch on the lever and the hammer is released. Under the action of the firing spring, which bears against the lower end of the hammer through a thrust pin, the hammer is driven forward striking the firing pin which, in turn, fires the primer.

For firing electrically, one side of the circuit is connected to a terminal, at the top of the hammer, attached to a contact piece insulated from the rest of the hammer. This contact piece makes contact with the primer through the firing pin, which is itself insulated from its surrounding parts. The other side of the circuit is grounded to the gun.

The combination *percussion-electric primer*, to be described in a subsequent chapter is used.

The slightest withdrawing of the slide from the closed position removes the firing pin from the percussion cap of the primer and precludes firing either electrically or by percussion.

200. Automatic and Semi-automatic Breech Mechanisms.—In guns provided with automatic breech mechanisms the energy of recoil or the pressure of the powder gases is utilized to open the breech, withdraw the fired cartridge case, insert a new cartridge, and close the breech. After the firing of the first round the only hand operation necessary for the firing of succeeding rounds is that of continuing to pull the trigger. The automatic mechanism is applied at present only to guns of small caliber that use the small-arms cartridge or fire a projectile weighing not more than a pound. The breech mechanisms of machine guns are examples of the full automatic type.

Semi-automatic breech mechanisms are those in which some of the

operations of opening or closing the breech, and of loading or extracting the cartridge, are done by hand and others are done automatically. The semi-automatic mechanism is applied to guns of medium caliber, and is especially applicable for antiaircraft guns.

Example of Semi-automatic Mechanism.—The breech mechanism of the 3-in. Antiaircraft Gun, Model of 1917, will be used to illustrate

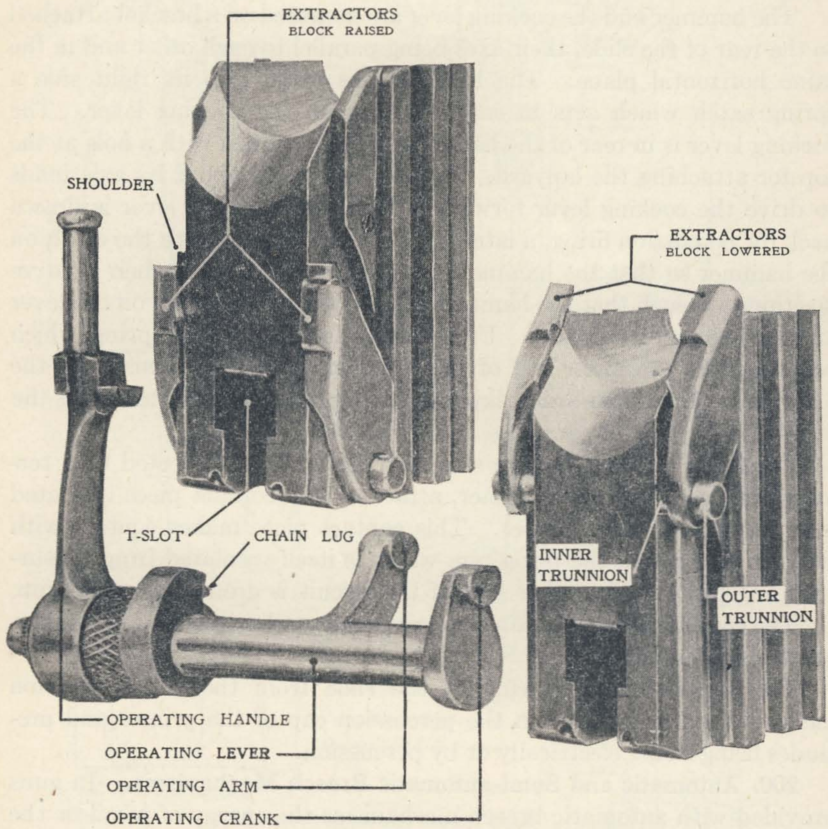


FIG. 94.—Breechblock and Operating Lever, 3-in. Antiaircraft Gun, Model of 1917. (Block shown in closed and in open positions.)

mechanisms of the semi-automatic type. The breech is opened automatically during the counter-recoil of the gun, and closes automatically when a round of ammunition is inserted by hand.

The breech mechanism, shown in Figs. 94, 95, and 96, is of the drop-block, or vertical sliding-wedge type. The block is rectangular in section. It slides up and down in the breech recess, under the action

of the operating arm which acts as an oscillating crank in raising and lowering the block. On each side of the block are two vertical slots which engage with corresponding flanges on the sides of the breech recess. These slots are inclined at a slight angle to the vertical, so that the block moves slightly forward in closing and forces the cartridge into its seat. The upper part of the block is cut away, to permit insertion of the cartridge in the chamber when the breech is open. The front end of the cut-away part is beveled. If the cartridge is not seated when the block is closed, the bevel will strike the edge of the cartridge case and push it home. A T-shaped slot is contained in the lower part of the block, Fig. 94, the slot being inclined upward toward the front face of the block. The T-shaped end of the operating arm, when rotated, works in this slot and raises and lowers the block.

The operating arm, Fig. 95, is an integral part of the operating lever, which is mounted to rotate in horizontal bearings locked to the breech of the gun. The operating crank of the lever is on its left end and the operating handle is attached to its right end, Figs. 94 and 95. By means of a clutch, the handle may be disengaged during automatic action of the block. The closing chain is attached to the chain lug on the operating-lever shaft. The closing spring, acting on the chain, tends to rotate the operating lever and raise the block to its closed position.

There are two extractors, one on each side of the front face of the breechblock. Extractor trunnion slots are cut in both sides of the breech recess and form seats for the outer extractor trunnions. Each extractor also has another trunnion on the inside of its lower portion, which operates in the extractor trunnion slot in the side of the block. As the block drops, rearward motion is given to the top of the extractors which eject the cartridge case. A flat surface is cut on each inner extractor trunnion, which engages with a corresponding horizontal shoulder at the top of the extractor trunnion slot. This arrangement locks the block open in its lowered position.

The operating cam, Fig. 95, suitably mounted on the left side of the cradle, works in conjunction with the operating crank to open the breech automatically during counter-recoil. The cam is so mounted that it can rotate to the rear but cannot rotate to the front of its vertical position.

Operation.—When the gun recoils after firing, the operating crank is in a vertical position. It moves to the rear with the gun and strikes the operating cam. The cam rotates backward until clear and then, under the action of a torsion spring, returns to its vertical position. In counter-recoil the operating crank strikes against the rigid cam. The

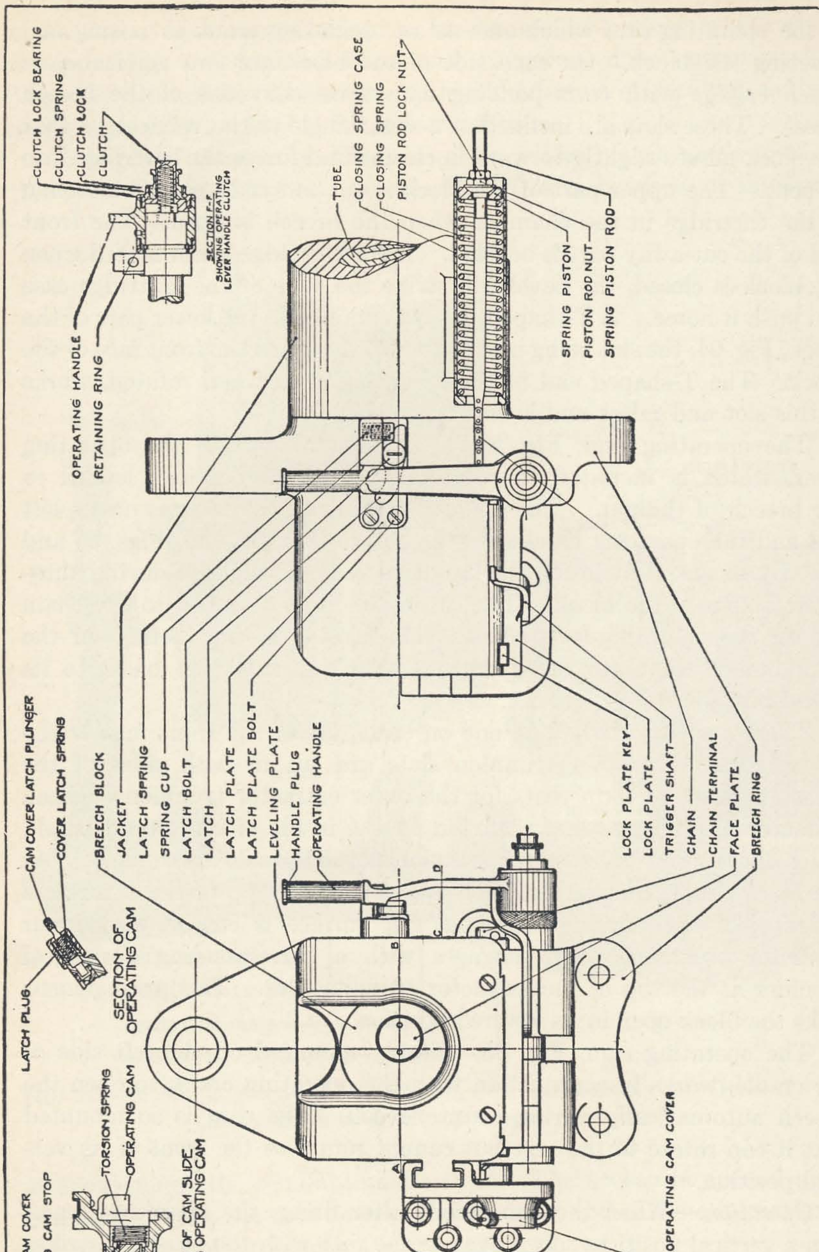


FIG. 95.—Breech Mechanism, 3-in. Antiaircraft Gun, Model of 1917. Rear and Right Side.

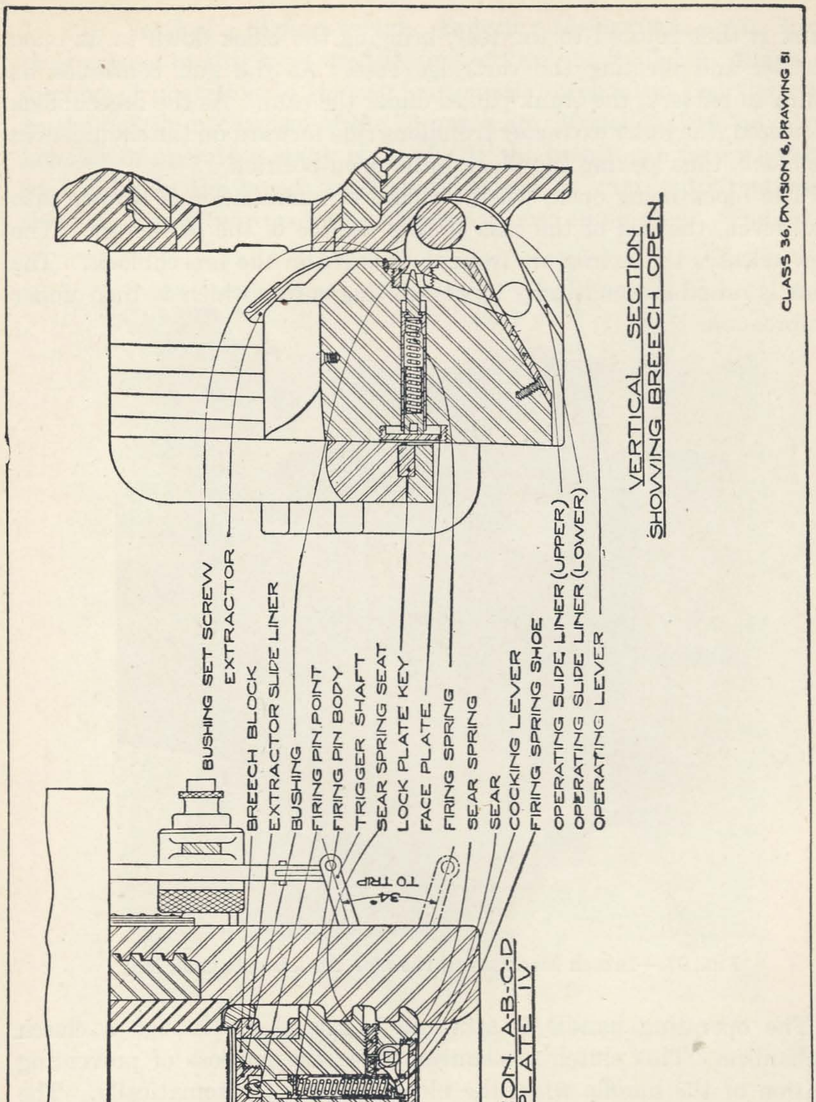


FIG. 96.—Breech Mechanism, 3-in. Antiaircraft Gun, Model of 1917. Horizontal and Vertical Sections.

crank is thus rotated to the rear, bringing the block down to its open position and ejecting the cartridge case. As the gun continues its return to battery, the crank passes under the cam. As the breechblock is lowered, the inner extractor trunnions ride forward on the shoulders in the block, thus locking the block in its open position.

The block being open, when a round of ammunition is thrown into the breech, the rim of the case strikes the toe of the extractors. The blow releases the extractors from their seats on the breechblock. The block is raised automatically by the closing spring which is then under compression.

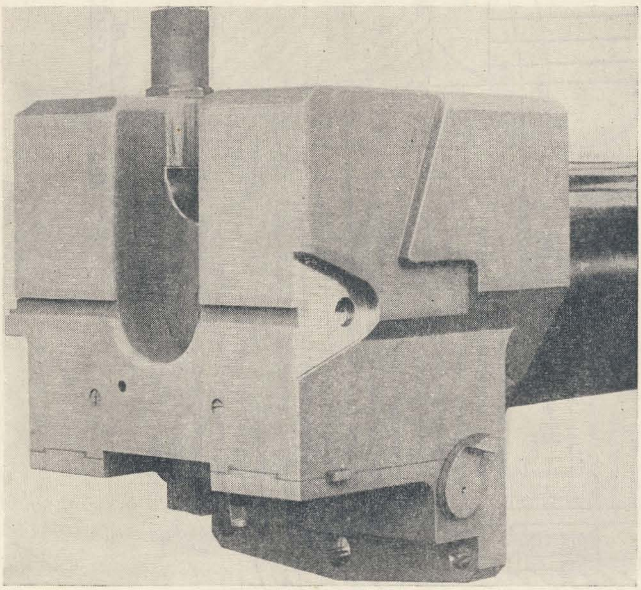


FIG. 97.—Breech Mechanism, 105-mm. Antiaircraft Gun, M1.

The operating handle is attached to the shaft through a clutch mechanism. This clutch mechanism is for the purpose of preventing rotation of the handle when the block is opened automatically. The clutch is disengaged and the handle remains vertical and caught by the latch for automatic action.

For hand operation, the clutch is engaged, locking the operating handle to the shaft, and the cam is locked down and held out of the path of the crank on the left end of the operating shaft. To open the breech, the operating handle is pulled back and down until the extractors lock the block in the lowered position. The handle is then pushed forward into the vertical position where it is caught by the latch.

201. Vertical Sliding-wedge Breech Mechanism.—All breech mechanisms of this type used in our service are similar in design and method of operation to the semi-automatic mechanism just described. In the breech mechanism of the 75-mm. Gun, Model of 1916, no operating cam or operating crank is provided; the breech can be opened only by hand. In the breech mechanism of the 105-mm. antiaircraft gun, shown in Fig. 97, the operating handle has been eliminated. The closing

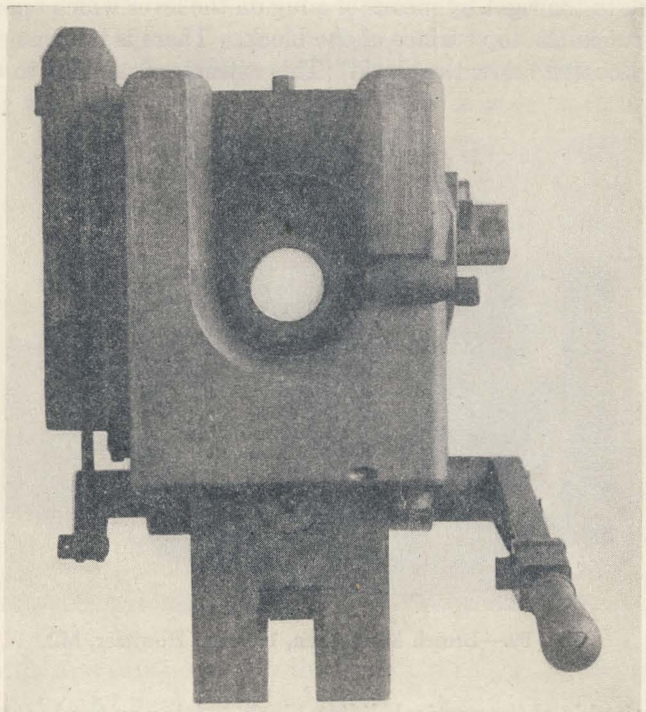


FIG. 98.—Breech Mechanism, 75-mm. Gun, M1.

spring on this mechanism is housed in a vertical position. However, the method of closing and the form of block and extractors described above have been preserved in both these mechanisms.

The breechblock used on the 75-mm. Gun, M1, is shown in Fig. 98. Although this is no longer a standard weapon, it illustrates the use of a vertical sliding block containing no automatic features. The block is mounted in a vertical slot cut in the rear part of the breech ring. It is raised or lowered to close or open the breech by means of the handle and

operating shaft. For ease in operation, the block is counterbalanced by a vertical spring mounted on the left side of the breech and connected to a crank on the left end of the operating shaft.

202. Horizontal Sliding-wedge Breech Mechanism.—The breech mechanism of the 105-mm. howitzer is an example of the horizontal sliding-block type. It is shown in Fig. 99. The breech is opened and closed by an operating lever pivoted in the upper part of the breech ring on the right side. Unlatching the lever and pulling to the right draw the block to the right by means of a lug on the lever which operates in a groove cut in the top surface of the block. There is but one extractor, which is located below the block. This extractor is similar to that used

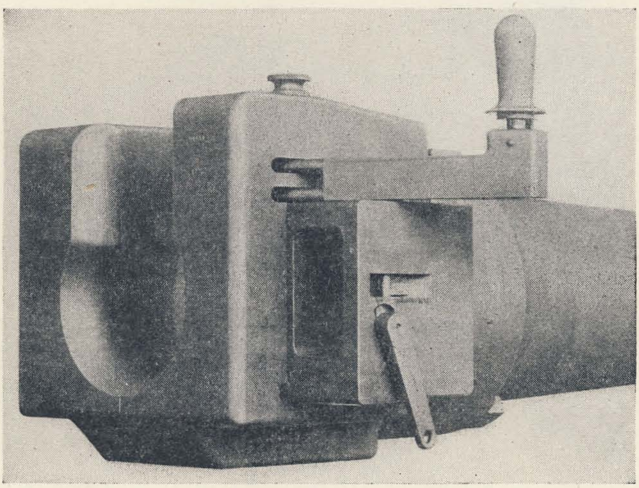


FIG. 99.—Breech Mechanism, 105-mm. Howitzer, M2.

on the left side of the vertical sliding block. A lug on the bottom side of the extractor is journaled in a curved slot in the breech recess. When the block is drawn to the right, a groove in the bottom surface of the block moves over a lug on the top of the extractor, and the extractor is operated and ejects the case.

The breech mechanism of the 75-mm. pack howitzer (see Chapter VIII) is of the horizontal sliding-block type. The block itself is supported in a horizontal recess cut through the rear part of the breech ring, which is detachable as shown. The operating lever is pivoted in the ring above the recess. As it swings on its pivot, a lug on the bottom of the lever sliding in a slot in the top of the block causes its horizontal movement to open or close the breech.

203. The Continuous-pull Firing Mechanism.—The firing mechanism used with modern field and antiaircraft artillery is of the "continuous pull" type; that is, the compressing and releasing of the firing pin spring are both effected by a continuous pull on the lanyard or trigger shaft. The firing pin spring is fully compressed only at the moment of firing. In case of misfire the blow of the firing pin can be repeated without opening the breech.

The Firing Lock, M13, illustrated in Fig. 100 is typical of this type of mechanism and is used on such weapons as the 75-mm. pack howitzer and the 3-in. antiaircraft gun. It consists of the following parts, as shown in Fig. 100: the trigger fork (1), the firing pin holder sleeve (2), the firing pin spring (3), the spring-supported sear (4) with its sloping

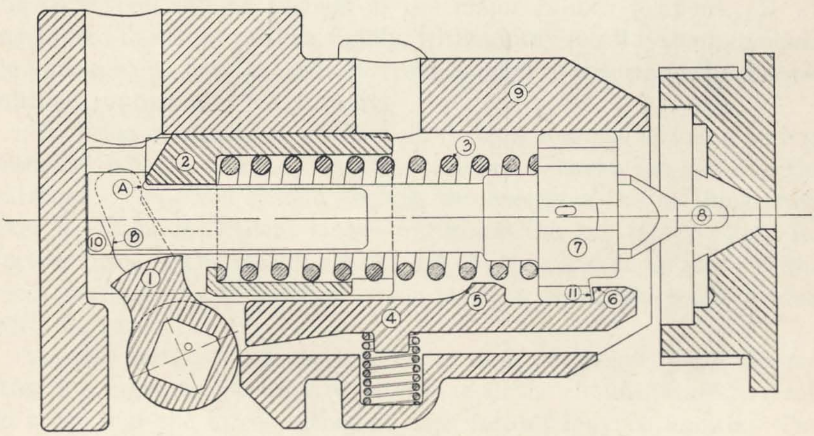


FIG. 100.—Firing Lock, M13.

shoulder (5) and sear notch (6), the firing pin holder (7), the firing pin (8), and the firing mechanism housing (9).

On firing the piece, the lanyard pull rotates the trigger backward and at the same time pushes the trigger fork (1) forward. This movement forces the firing pin holder sleeve (2) forward and compresses the spring until the sleeve rides the slope (5) of the spring-supported sear and forces it downward. This disengages the sear from its seat (11) on the firing pin holder (7), releases the latter (with firing pin (8) assembled), and fires the piece.

On release of the lanyard, the firing pin returns automatically to its rearward position. The spring, being still compressed, forces the firing pin holder sleeve backward. The firing pin holder sleeve pushes back on the trigger fork at (*A*). The spring exerts an equal pressure forward

on the firing-pin holder and this force is transmitted to the trigger fork at (B). Therefore, with equal forces acting, since the lever arm from O to A is longer than that from O to B, the trigger fork and trigger return to their original position.

The backward movement of the firing pin holder sleeve permits the sear to rise, engage its seat on the firing pin holder (11), and the mechanism is ready to operate again.

CHAPTER VII

THE THEORY OF RECOIL AND RECOIL SYSTEMS

204. Stresses on the Gun Carriage.—The stresses to which a gun carriage is subjected are due to the action of the powder gases on the gun itself. As the powder gas pressure is transmitted equally in all directions, the force tending to move the gun to the rear is very large, amounting to several million pounds in the major caliber weapons. If we attempted to mount the gun rigidly, without any recoil system, it would be impossible to build a carriage strong enough to withstand the stresses without rupturing or overturning.

To bring the carriage stresses down to a reasonable value and to insure stability, a recoil system is interposed between the gun and the carriage. The recoil system absorbs the energy of the recoiling parts over a certain convenient length, returning the gun into position for further firing. The recoiling parts are the gun and those parts of the recoil mechanism and carriage which move in recoil and counter-recoil with the gun.

As gun carriages are constructed to limit the recoil to the desired length, it becomes necessary to determine all the circumstances of recoil in order that the forces acting at each instant may be known. The parts of the carriage, then, may be designed to withstand these forces and to absorb the recoil in the desired length. The circumstances of *retarded recoil* cannot be determined easily or directly; the hypothetical problem of *free recoil* must be solved first.

205. Velocity of Free Recoil.—*Free recoil* assumes that the gun is mounted so that it may recoil freely in a horizontal direction; that is, without any resistance. On explosion of the charge, the parts of the system acted upon by the powder gases are the gun, the projectile, and the powder charge itself, the powder charge including at any instant both the unburned and the gaseous portions. While the projectile is in the bore, if we neglect the resistance of the air, none of the energy of the powder gases is expended outside the system; and the momentum of the moving gun is equal and opposite in direction to the momentum of the projectile and powder charge. Therefore, we may write

$$Mv_f = mv + \mu v_c \tag{1}$$

in which M, m, and μ are the masses of the gun, projectile, and charge of powder, respectively; and v_f, v, and v_c the velocities of the same parts. The mass of the charge is the same whether the charge is unburned or partially or wholly burned.

The velocity of the projectile at any point in the bore of the gun may be determined from the formulas of interior ballistics.

As in interior ballistics, it is assumed that the velocity of the center of the mass of the products of combustion is half the velocity of the projectile.

Writing $v/2$ for v_c in Eq. (1), replacing masses by weights, and solving for v_f, we obtain

$$v_f = \frac{p + \frac{1}{2}c}{W} v \tag{2}$$

W, p, and c being the weight of the gun, projectile, and charge, respectively. At the muzzle of the gun v becomes the initial velocity, V, and for the velocity of free recoil at that instant,

$$v_f' = \frac{p + \frac{1}{2}c}{W} V \tag{3}$$

This value v_f' is not the *maximum* velocity of free recoil, though it is the maximum value reached while the gun and the projectile are connected. At the departure of the projectile, the bore of the gun is still filled with expanding gases, which continue to exert pressure on the breech and increase the velocity of recoil. The maximum velocity of free recoil, represented by V_f, must be determined by other means since Eq. (1) does not hold true if the parts of the system (gun, projectile, and charge) are separated. Experiments with the Sebert velocimeter indicate that the maximum velocity of free recoil may be obtained from Eq. (3) by substituting for the quantity $\frac{1}{2}cV$ the quantity $4700c$. This is equivalent to assuming that the center of mass of the powder gases leaves the muzzle with a velocity of 4700 ft. per sec.; Eq. (3) then becomes

$$V_f = \frac{pV + 4700c}{W} \tag{4}$$

The value of v_f' is about $\frac{7}{10} V_f$.

206. Determination of the Circumstances of Free Recoil.—In the above equations the velocity of free recoil is expressed as a function of the velocity of the projectile, and we have in the formulas of interior

ballistics the velocity of the projectile expressed as a function of the travel of the projectile in the form:

$$v = \frac{au}{b + u}$$

The *velocity of free recoil* as a function of *travel of projectile* might now be determined.

Before the design of a recoil mechanism can be completed, the relations between velocity, time, and length of recoil must be known; and in order to arrive at these relations by the use of Eq. (2), the only means available, we must obtain an expression for the velocity of the projectile as a function of time.

The outline of the process for passing from Eq. (2), in which v_f is expressed in terms of v, to the curve of Fig. 102, in which v_f is shown as a function of t, is as follows:

From Eq. (2),	$v_f = f(v)$	(*a*)
From interior ballistics,	$v = f(u)$	(*b*)
But, since $v = \frac{du}{dt}$	$t = \int \frac{1}{v} du$	(*c*)
From (*b*),	$\frac{1}{v} = f_1(u)$	(*d*)
Therefore,	$t = f_2(u)$	(*e*)
From (*b*) and (*e*),	$v = f(t)$	(*f*)
Therefore,	$v_f = f_1(t)$ Q.E.D.	(*g*)

$f(u), f_1(u)$, and $f_2(u)$ represent different expressions in u.

Velocity of Projectile as a Function of Time.—With the velocity of the projectile expressed as a function of the time, Eq. (2) will then express the velocity of free recoil as a function of the time; and with the velocity of recoil so expressed we may obtain the length of free recoil from the equation

$$x = \int v_f dt \tag{5}$$

x representing the length of free recoil.

We thus obtain the complete relations between velocity, time, and length of free recoil.

The velocity of the projectile as a function of the time is obtained

in the following manner. Representing the travel of the projectile by u, we have

$$v = \frac{du}{dt}, \text{ from which } t = \int \frac{1}{v} du \qquad (6)$$

That is, t is the area under the curve whose ordinates are values of $1/v$ and whose abscissae are values of u.

Therefore, if we construct such a curve, the area under the curve from the origin to any ordinate will be the time corresponding to the velocity whose reciprocal is represented by the ordinate.

Construct the curve v, Fig. 101, from Le Duc's equation,

$$v = \frac{au}{b + u}$$

the abscissae representing travel and the ordinates representing velocity of the projectile.

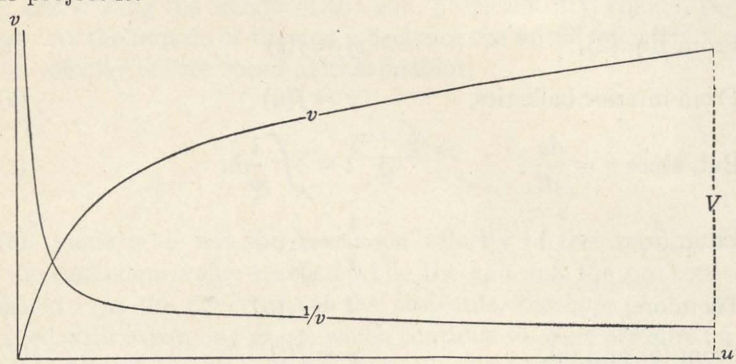


FIG. 101.

Take the value of v as expressed by any ordinate and lay off its reciprocal on the same ordinate, to any convenient scale. The curve $1/v$ in the figure is obtained in this way. Its ordinates are values of $1/v$, its abscissae are values of u. The areas under the curve are therefore values of t, Eq. (6).

For very small values of v the ordinates $1/v$ will be very large and will not fall within the limits of an ordinary drawing. Consequently we cannot determine the exact area under the first part of the curve. But we can obtain a sufficiently close approximation to this area in the following manner. We may assume, without material error in the determination of this small area, that the velocity of the projectile as a function of the time is expressed by the equation of a parabola

$$v = \sqrt{2kt} \qquad (7)$$

Multiplying by dt and integrating, we have, since $\int v\,dt = u$,

$$u = \int \sqrt{2kt}\,dt = \tfrac{2}{3}(2k)^{1/2}t^{3/2} \tag{8}$$

At the instant at which the shot leaves the bore, v in Eq. (7) becomes the initial velocity V, and denoting the corresponding time by t' we obtain from that equation

$$V = \sqrt{2kt'} \quad \text{or} \quad \sqrt{2k} = \frac{V}{\sqrt{t'}}$$

Substituting this value of $(2k)^{1/2}$ in Eq. (8), t in that equation becoming t' and u, the total travel of the projectile, U, we obtain

$$t' = \frac{3}{2}\frac{U}{V}$$

Under this assumption, t' is the total area under the curve $1/v$, Fig. 101; and subtracting from t' the area that can be measured, we obtain the area under that part of the curve near the origin that is not plotted.

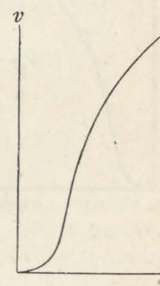


FIG. 102.

Having now from the v curve the values of $v = f(u)$ and from the areas under the $1/v$ curve the values of $t = f(u)$, we may, by combination, determine the desired values of $v = f(t)$.

Using as abscissae the areas under the curve $1/v$, which are the values of t, and as ordinates the corresponding ordinates of the curve v, which are the velocities, we obtain the curve of the velocity of the projectile as a function of the time, Fig. 102.

The velocity of free recoil (v_f), as given by Eq. (2), is equal to the velocity of the projectile (v) multiplied by the constant,

$$\frac{p + \frac{1}{2}c}{W}$$

The ordinates in Fig. 102 represent values of v. If now we consider the scale of ordinates to be multiplied by

$$\frac{p + \frac{1}{2}c}{W}$$

the ordinates become values of v_f; and we have at once the curve of v_f as a function of t.

207. Maximum Velocity of Free Recoil.—The curve shown in Fig. 102 gives the velocity of free recoil only while the projectile is in the

bore; and, as previously explained, the velocity of recoil has not reached its maximum when the projectile leaves the piece. The value of the maximum velocity of recoil is given by Eq. (4). With this value as an ordinate, Fig. 103, draw a line parallel to the axis of t and continue the curve of velocity already drawn until it is tangent to this line. It is reasonable to infer that the rate of change in the curvature of the curve of recoil will continue uniform from the point corresponding to the muzzle of the gun to the point of maximum velocity, and the curve so continued will with sufficient exactness express the circumstances of motion. A slight error made in the selection of the point of tangency will be without practical effect on the determinations to be later made from this curve. The abscissa of the point of tangency is the time corresponding to the maximum velocity of free recoil. It is also the

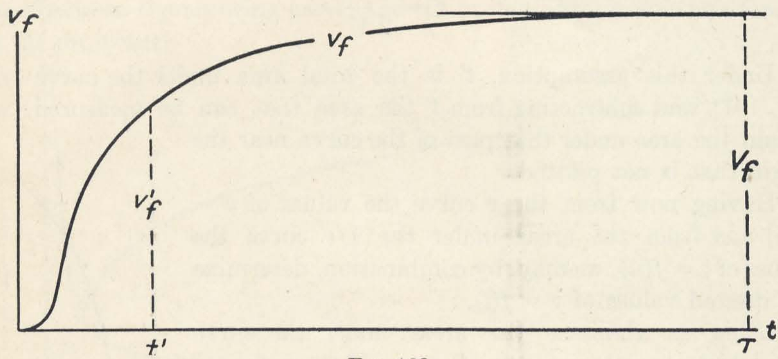


FIG. 103.

total time of action of the powder gases on the gun and is represented by τ.

As, by assumption, there is no resistance to recoil, the maximum velocity attained will never be reduced, and the curve will extend indefinitely parallel to the axis of t.

The tangent to the curve at any point is a value of dv_f/dt, and therefore represents the acceleration at the instant of time represented by the abscissa of the point. The tangent has a maximum value at the point of inflexion of the curve, the point where the curve ceases to be convex toward the axis of t, and becomes concave. This point is therefore the point of maximum acceleration. The maximum acceleration being due to the maximum powder pressure in the gun, the abscissa of the point of inflexion is the time of the maximum pressure.

From Eq. (5), $x = \int v_f dt$, therefore the area under the curve v_f,

Fig. 103, from the origin to any ordinate, is the length of free recoil corresponding to the velocity represented by the ordinate.

Representing by E_{f_τ} the area under the curve up to the time τ we have

$$E_{f_\tau} = \int_{t=0}^{t=\tau} v_f dt \tag{9}$$

208. Symbols.—The symbols used in the preceding discussion are here tabulated for reference:

W, p, c = weight of gun, projectile, and charge, respectively.
v = velocity of projectile at any point.
v_f = velocity of free recoil at any point.
v_f' = velocity of free recoil when the projectile leaves the muzzle.
V = initial velocity of the projectile (muzzle velocity).
V_f = maximum velocity of free recoil.
x = any length of free recoil.
t = any time of free recoil.
t' = time when projectile leaves the muzzle.
u = any distance of travel of projectile in the bore, in feet.
U = travel of projectile to the muzzle.
τ = total time of action of powder gases on gun.
E_{f_τ} = length of free recoil at the time τ.

PROBLEMS

1. The recoiling parts of a 3-in. gun weigh 950 lb. The weights of projectile and charge are 15 lb. and 1.5 lb., respectively. The muzzle velocity is 1700 ft. per sec.

Determine the velocity of free recoil at the time the projectile reaches the muzzle and the maximum velocity of free recoil.

2. The maximum pressure in the field gun referred to in Problem 1 is 32,000 lb. per sq. in. The travel of the projectile at the muzzle is 74.54 in. Assume $a = 2125$, $b = 1.55$.

Using Le Duc's formulas for velocity and maximum pressure, determine the velocity of the projectile as a function of the travel for travels of 12, 24, 48, and 60 in., and plot the curve of velocity as a function of travel.

3. From the plotted curve in Problem 2, determine and plot the curve of reciprocals of velocity as a function of the travel.

4. From the data in Problems 2 and 3, determine and plot the curve of velocity of the projectile as a function of the time. Determine also the scale of velocity to be used so that the plotted curve may represent the curve of velocity of free recoil as a function of the time.

5. From the plotted curve in Problem 4, determine τ and E_{f_τ}.

209. Retarded Recoil—Total Resistance to Recoil Constant.—In the discussion thus far, we have neglected all resistances and have considered the movement of the gun in recoil as unopposed. When

the gun is mounted on a carriage, the recoil brakes begin to act as soon as recoil begins and, consequently, the velocity of recoil is less at each instant than the velocity shown by the curves just determined.

It is evident that the higher the resistance offered by the recoil brakes the shorter will be the total length of recoil. The system may be designed so that throughout recoil the total resistance offered will be the same at each instant, or the total resistance offered to recoil may be made variable. Since the work performed in each case is the same, the value of the constant total resistance will be less than the maximum value of a varying total resistance and, accordingly, for a given length of recoil the constant total resistance will produce less strain in the carriage.

In the following discussion, it will be assumed that constant total resistance is maintained throughout the recoil.

210. Relation between Length of Recoil and Constant Total Resistance to Recoil.—

Let M represent the mass of the gun and recoiling parts.

- F, the total pressure of the powder gases over the cross section of the bore at any time.
- R, the constant total resistance to recoil.
- τ, the total time the powder gases act on the gun.
- L, the total length of recoil.
- V_f, the maximum velocity of free recoil.
- V_r, the maximum velocity of retarded recoil.
- $v_{r\tau}$, the velocity of retarded recoil at the time τ.
- $E_{r\tau}$, the distance recoiled at the time τ with the resistance R acting.
- $E_{f\tau}$, the length of free recoil at the time τ.
- x, the distance recoiled at any time t.
- v_r, the velocity of retarded recoil at any time t.
- T, time required to bring gun to rest (total time of retarded recoil).

At any instant prior to the time the powder gases cease to act on the gun, we have, since force equals mass times acceleration,

$$M\frac{d^2x}{dt^2} = F - R \tag{10}$$

Multiplying by dt and integrating, we have

$$M\frac{dx}{dt} = \int Fdt - Rt \tag{11}$$

The constant of integration is 0, since $\frac{dx}{dt} = v_r = 0$ and $\int Fdt = Mv_f = 0$, when $t = 0$. Substituting these values in the above equation and

dividing by M, we have for any time t,

$$v_r = v_f - \frac{R}{M} t \tag{12}$$

and for the time τ,

$$v_{r\tau} = V_f - \frac{R}{M} \tau \tag{13}$$

When the gun has ceased recoiling, $v_r = 0$, $v_f = V_f$, and $t = T$. Making this substitution in Eq. (12) and solving for t, we have, for the time required to bring the gun to rest,

$$T = \frac{MV_f}{R} \tag{14}$$

By a second integration of Eq. (10), we have

$$Mx = \iint F dt \cdot dt - \frac{Rt^2}{2}$$

Here again the constant of integration is 0 since all terms vanish when $t = 0$. When $t = \tau$, $x = E_{r\tau}$ and $\iint F dt \cdot dt = \int_0^\tau M v_f dt = ME_{f\tau}$ by Eq. (9). Substituting these values in the above equation and dividing by M, we have, for the time τ,

$$E_{r\tau} = E_{f\tau} - \frac{R}{2M} \tau^2 \tag{15}$$

Since at the time τ and thereafter no force is acting on the gun except the constant resistance R, we may now equate the remaining energy of motion of the gun to the work of R over the remaining length of recoil. Doing this we obtain

$$R(L - E_{r\tau}) = \frac{Mv^2_{r\tau}}{2} \tag{16}$$

Substituting values of $v_{r\tau}$ and $E_{r\tau}$ from Eqs. (13) and (15) and solving for R, we obtain for the total constant resistance to recoil

$$R = \frac{MV_f^2}{2[L + (V_f \times \tau) - E_{f\tau}]} \tag{17}$$

from which we can determine the numerical value of R in terms of L or of L in terms of R.

In the design of a recoil brake, the permissible length of recoil is

often limited by the dimensions of the carriage, maximum angle of elevation, or other considerations. The path of recoil must then be limited by applying sufficient resistance by the brake to absorb the energy of recoil over that distance. This value of R can be determined from Eq. (17) when L is known.

211. Velocity of Retarded Recoil as a Function of Time and of Space.—Let x be the distance through which the gun has recoiled at any time t and let v_r be the velocity of retarded recoil at this time.

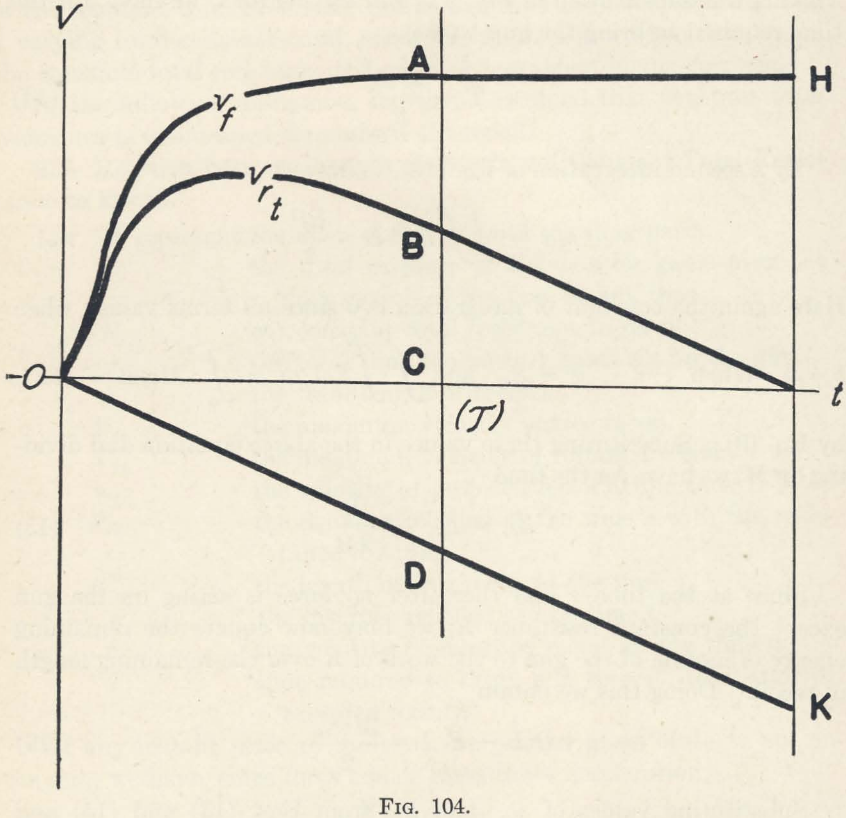


Fig. 104.

Since retardation (negative acceleration) is the rate of change of velocity, it may be expressed as $\frac{dv}{dt}$ or $\frac{R}{M}$ which is the rate at which velocity is being taken out of the system. The total velocity taken out of the system by R at any instant, therefore, will be given by the ordinate of a right line which passes through the origin of coordinates and makes an angle with the axis of t, whose tangent, when expressed in the units

of the axes, is $-\frac{R}{M}\cdot$ This line is indicated in Fig. 104 as the line OK. The curve OH in this figure represents the velocity of free recoil, plotted against time, and is similar to that shown in Fig. 103 except for the reduced scale of abscissae.

The velocity of retarded recoil, at any time t, is equal to the velocity of free recoil minus the loss in velocity; that is, the ordinate of any point on the v_{r_t} curve is equal to the algebraic sum of the ordinates to curves OH and OK. The curve v_{r_t} is the summation of the ordinates to these two curves.

The length of retarded recoil corresponding to any velocity of retarded recoil represented by an ordinate of the curve v_{r_t} is the area under the curve from the origin to the given ordinate.

We may now construct the curve of velocity of retarded recoil as a function of the distance recoiled. To construct a point of the curve,

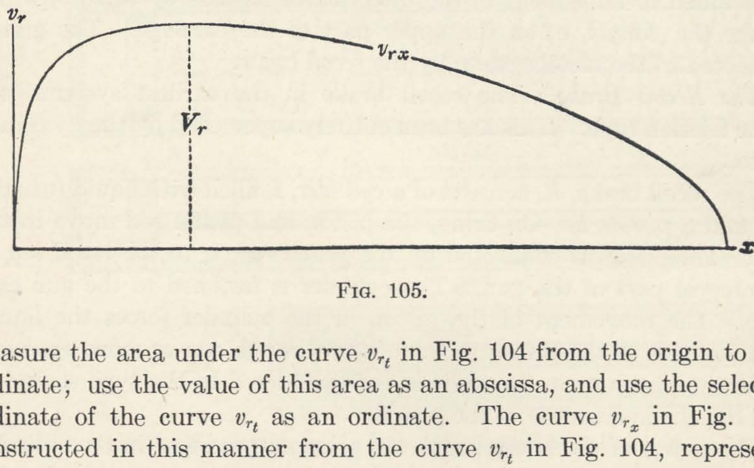


FIG. 105.

measure the area under the curve v_{r_t} in Fig. 104 from the origin to any ordinate; use the value of this area as an abscissa, and use the selected ordinate of the curve v_{r_t} as an ordinate. The curve v_{r_x} in Fig. 105, constructed in this manner from the curve v_{r_t} in Fig. 104, represents the velocity of retarded recoil as a function of the distance recoiled.

This same relation between the velocity of retarded recoil and distance of retarded recoil after the time τ can be obtained also from a consideration of the energy in the system. We have, as in obtaining Eq. (16),

$$R(L - x) = \frac{Mv_r^2}{2} \tag{18}$$

whence,

$$v_r = \sqrt{\frac{2R(L - x)}{M}} \tag{19}$$

This is the equation of a parabola with its vertex at $x = L$.

PROBLEMS

1. The total length of recoil of the field gun referred to in Problems 1 to 5, Section 208, is to be 45 in.

What constant resistance to recoil is required?

2. With the determined constant resistance to recoil acting, determine and plot the curve of velocity of retarded recoil as a function of the time.

3. From the curve obtained in Problem 2, determine and plot the curve of velocity of retarded recoil as a function of distance recoiled.

212. Recoil Systems.—The recoil system of a gun carriage consists of a *recoil brake*, *R*, for controlling the recoil and limiting its length, a *counter-recoil mechanism*, *C*, for returning the gun to firing position and keeping it there, and a *counter-recoil brake* or *buffer*, *B*, to diminish the shock as the gun returns to the firing position.

The gun, *G*, in recoiling, slides to the rear on its carriage. It is constrained to movement in the direction of its axis by *clips*, *b*, which engage the *flanges*, *a*, on the upper part of the carriage. The gun is connected to the recoil system by the *recoil lug*, *c*.

The Recoil Brake.—The recoil brake in the earliest systems was of the friction type. This has been entirely superseded by the hydraulic brake.

The recoil brake, *R*, consists of a *cylinder*, *i*, filled with liquid (usually oil), and a *piston*, *h*. On firing, the piston and piston rod move to the rear. The piston is connected by the *piston rod*, *k*, to the *recoil lug*, *c*, an integral part of the gun. The cylinder is fastened to the gun carriage. The movement of the piston in the cylinder forces the liquid from one side of the piston to the other, through one or more *apertures* cut in the piston or in the walls of the cylinder. In the type shown in Fig. 106 the aperture is in the piston.

The power of the brake lies in the pressure produced in the cylinder by the resistance offered by the liquid to motion through the aperture. The work done by the liquid in bringing the piston to rest at the end of recoil must equal the energy of the moving parts; or $\frac{mv^2}{2} = Fs$, where F is the mean pressure exerted by the liquid on the piston. If the area of the aperture is constant, it is evident that the resistance to flow will be greater as the velocity of the piston (or the velocity of recoil) is greater. Therefore the pressure in the cylinder, which measures the resistance offered, will vary with the different values of the velocity of recoil. If, however, the apertures are constructed in such a manner that the area of aperture increases when the velocity of the piston increases and diminishes when the velocity diminishes, the variation in

the area of aperture may be so regulated that the pressure in the cylinder will be constant throughout recoil, or will vary in such a manner as to keep the total resistance to recoil constant, or to make it vary in any manner desired.

A variable area of the aperture is accomplished by different mechanical devices. One method is shown below. The *throttling bar, l,* of varying cross section, is fastened to the walls of the cylinder and the piston is provided with corresponding apertures. The aperture has

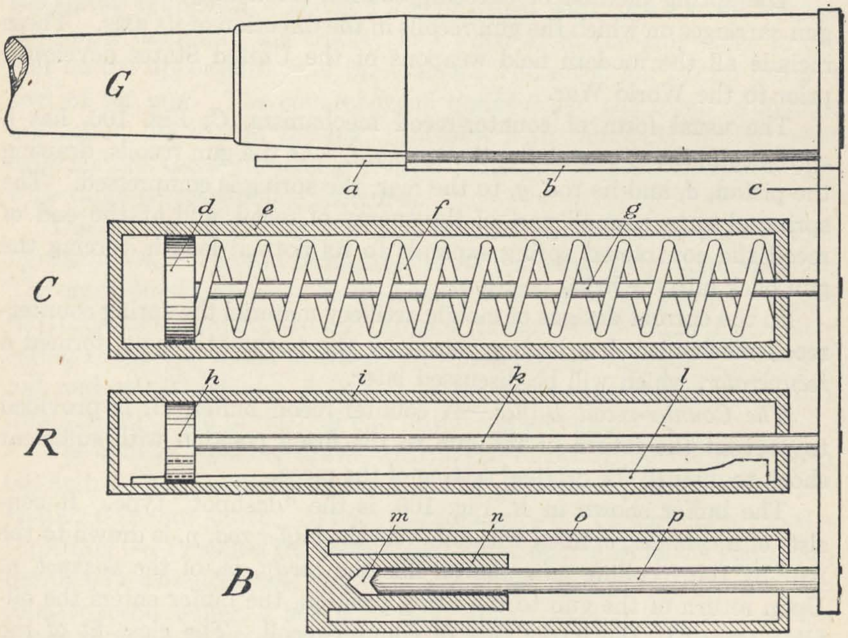


FIG. 106.—Hydro-spring Recoil System (Schematic).

the dimensions of the maximum section of the throttling bar, with just enough clearance to permit operation. The area open to the flow of liquid at any position of the piston is therefore equal to the area of the aperture minus the area of cross section of the throttling bar at that point. This opening is called the *orifice.* The profile of the throttling bar is so determined that the resistance to the flow of the liquid is made constant or variable as desired.

Another method of obtaining the varying orifice dispenses with the aperture in the piston. Instead of the throttling bar, a *throttling groove* of varying width or depth is cut on the interior of the cylinder.

The Counter-recoil Mechanism.—Counter-recoil, or the return of

the gun to the firing position after the completion of recoil, may be effected by gravity, by springs, or by compressed air or gas.

The gravity method of effecting counter-recoil is the simplest and can always be used when the direction of motion of the recoiling parts is such as to cause a continual rise in their center of gravity as they move to the rear. The gravity method is used in old-type barbette carriages, now obsolete, and in the obsolescent disappearing carriages of the coast defenses.

The spring method of effecting counter-recoil may be used on all gun carriages on which the gun recoils in the direction of its axis. These include all the modern field weapons of the United States developed prior to the World War.

The usual form of counter-recoil mechanism, *C*, Fig. 106, has a *spring cylinder*, *e*, containing the *spring*, *f*. As the gun recoils, drawing the piston, *d*, and its rod, *g*, to the rear, the spring is compressed. The spring absorbs a small part of the energy of recoil, and at the end of recoil the contracted spring expands to its normal length, forcing the gun back into the firing position.

In the current designs of mobile artillery materiel the spring counter-recoil mechanism has been replaced by the pneumatic type, termed a *recuperator*, which will be discussed later.

The Counter-recoil Buffer.—A counter-recoil buffer, *B*, is provided to prevent the return of the gun to the firing position with sufficient shock to disturb the original setting of the piece.

The buffer shown in *B*, Fig. 106, is the "dashpot" type. It consists of a *cylinder*, *o*, filled with oil. As the *buffer rod*, *p*, is drawn to the rear by the recoiling gun, the oil fills the *cavity*, *m*, of the *dashpot*, *n*. Upon return of the gun to the firing position, the buffer enters the oil-filled cavity in the latter part of counter-recoil. The close fit of the buffer rod in the dashpot permits the oil to flow out through only a small orifice, and the motion of the buffer in its last few inches of forward movement meets great resistance. The gun is thus eased into firing position without jarring the carriage. A modification of this type is called a *spearhead* buffer.

213. The Hydrospring System.—A recoil system in which the counter-recoil operation is performed by a spring is termed a *hydrospring recoil system*. Such a system is illustrated in Fig. 106, where each member is shown separately. In actual practice such bulky design is obviated by grouping the members around the gun. The most compact arrangement is obtained by a concentric grouping of buffer, brake, and spring, housing the entire mechanism in a cradle which supports the gun. The latter method was employed in the U. S. 3-in.

Field Gun, Model 1902, and the British 75-mm. Field Gun, Model 1917.

The 3-in. Field Gun Recoil System.—The hydrospring recoil system of the 3-in. field gun is shown in Fig. 107, in partial recoil and "in battery" (returned to firing position). The longitudinal section is drawn to a distorted scale in order to show the parts more clearly.

A cylindrical cradle is fastened to the gun carriage and contains the spring cylinder *a*. The gun *n* is provided with clips *r* which engage the upper flanges of the cradle; and when fired, the gun slides to the rear on the upper surface of the cradle. The recoil lug *f* is an integral part of the gun. The counter-recoil buffer *k* and the recoil cylinder *e* are bolted directly to the lug. Integral with the walls of the recoil cylinder are three throttling bars *i*. The piston head *h* is provided with three corresponding apertures.

The hollow piston rod *g* is held to the front of the spring cylinder by the nut *m*. The rod terminates at its rear end in the piston head *h*. The outer shoulder formed on the front end of the recoil cylinder receives the thrust of the counter-recoil springs *d* transmitted through the annular spring support *c*, which also serves to preserve the alignment of piston rod and recoil cylinder in recoil. The flat coiled spring *d* extends from the front end to the rear end of the recoil cylinder.

The gun in recoiling draws with it the recoil cylinder *e* filled with oil, and the counter-recoil buffer *k*. The piston rod *g*, attached to the cradle, does not move. When the forward end of the curve of the throttling bar *i* reaches the piston head *h*, the apertures in the piston are completely closed against the flow of the oil, and recoil ceases. The counter-recoil buffer *k* has now been drawn all the way out of the piston. The dashpot *l* fills with oil.

Under the action of the springs *d*, which have been compressed by the recoil, the gun returns to battery. The first part of the counter-recoil, during which the counter-recoil buffer is out of the dashpot, is unobstructed. When the buffer enters the hollow piston rod, the escape of oil from inside the dashpot is permitted only through the narrow clearance between the rod and buffer. The resistance thus offered gradually diminishes the velocity of counter-recoil as the gun comes into battery and brings it to rest without shock.

The recoil system of the British 75-mm. Field Gun, Model 1917, is essentially the same as that of the U. S. 3-in. Field Gun, Model 1902, just described. The main difference is the location of the cradle and recoil mechanism with respect to the gun. The recoil system of the 37-mm. Gun, Model 1916 (1-pounder), is of a similar type.

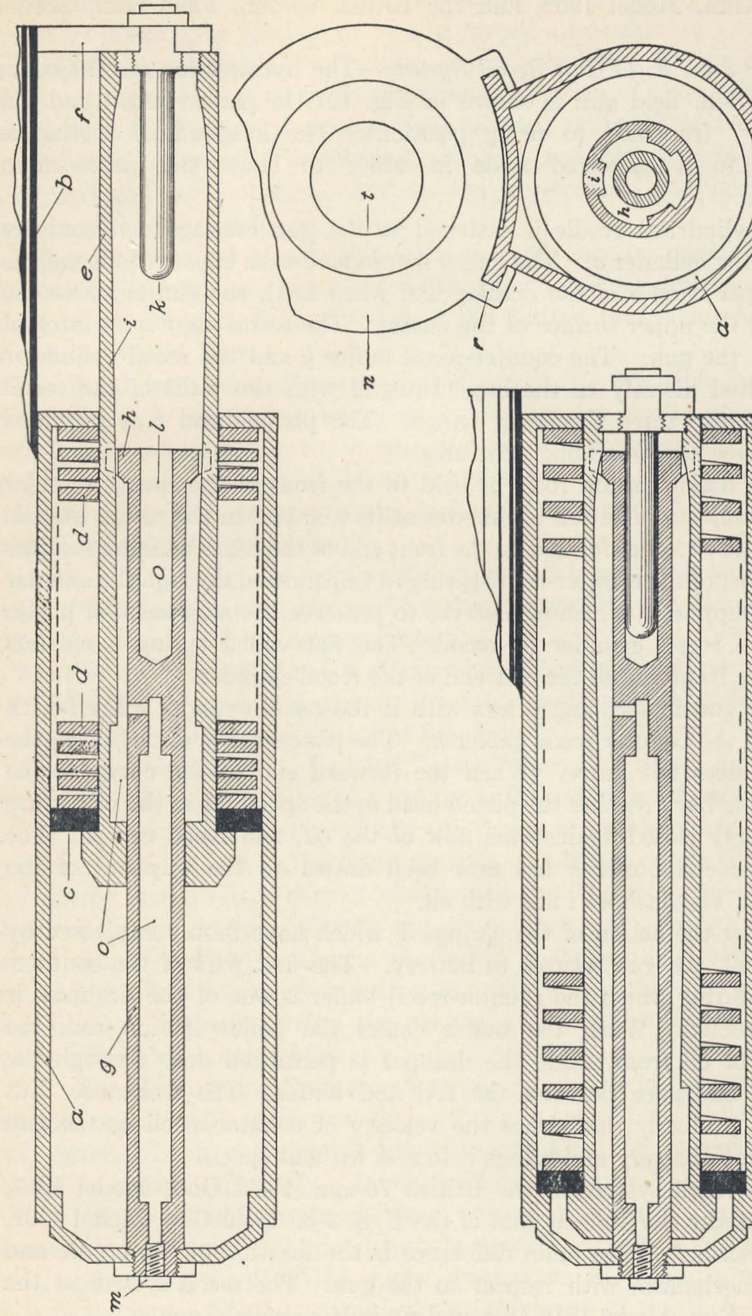


FIG. 107.—Recoil System for U. S. 3-in. Field Gun, Model of 1902.

214. Hydropneumatic Recoil Systems.—During the World War the United States replaced its light and heavy field guns and howitzers by those of current French design. These employed the *hydropneumatic* recoil system, in which the hydraulic recoil brake and the buffer remain essentially the same but the force of compressed air or nitrogen (instead of a helical spring) returns the gun to its firing position after recoil. Dry nitrogen instead of air is generally used, as it prevents

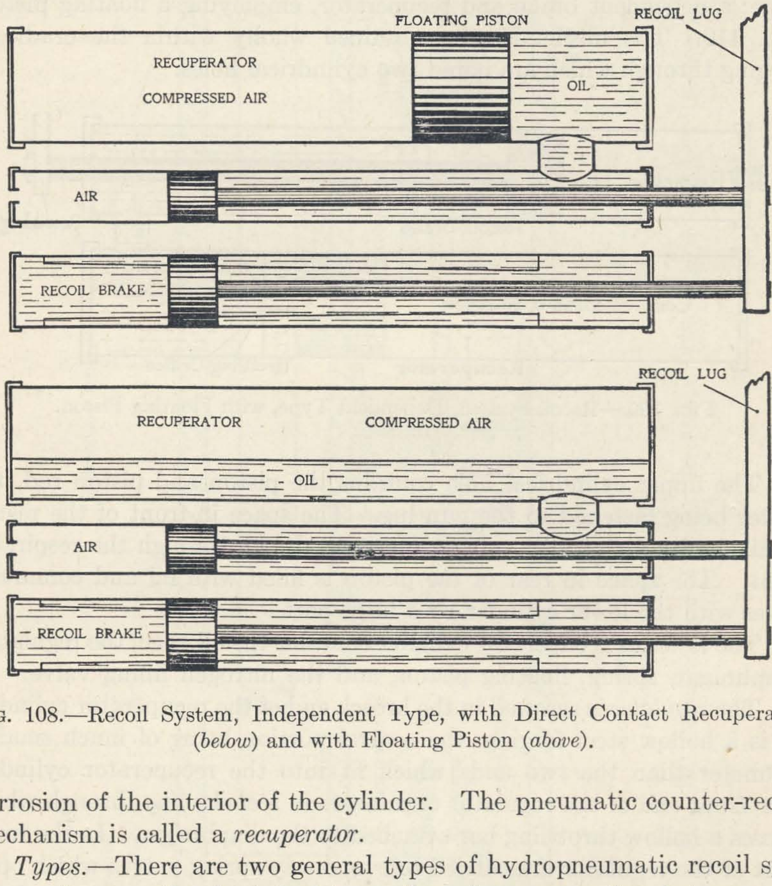


FIG. 108.—Recoil System, Independent Type, with Direct Contact Recuperator (*below*) and with Floating Piston (*above*).

corrosion of the interior of the cylinder. The pneumatic counter-recoil mechanism is called a *recuperator*.

Types.—There are two general types of hydropneumatic recoil systems. In one, the *dependent* type, there is a connection between the hydraulic recoil brake and the compressed air counter-recoil cylinders, whereas in the other the brake and recuperator are entirely *independent* of each other.

Variations in the design of the recuperator in each type of system are the basis for another grouping. The *direct contact* recuperator, containing both oil and compressed air, has the fluid directly in contact

with the air. The *floating piston* recuperator employs a freely moving piston to separate the oil from the air mechanically.

The French 75-mm. Field Gun, Model 1897, has the dependent system with floating piston. The Schneider 155-mm. Howitzer, Model 1918, employs the independent direct contact system.

215. French 75-mm. Recoil System (Puteaux).—The recoil system of the 75-mm. Field Gun, Model 1897 (French), is the hydropneumatic type; a dependent brake and recuperator, employing a floating piston, Fig. 110. The mechanism is contained wholly within the cradle, a forging through which are bored two cylindrical holes.

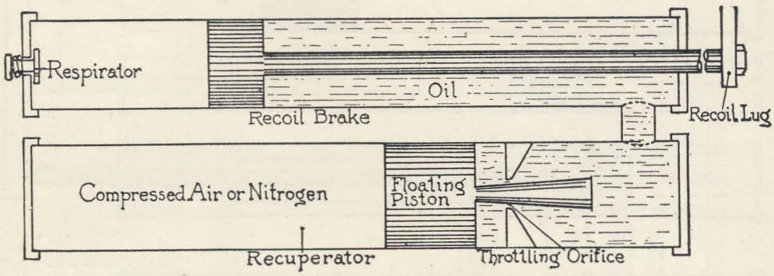


FIG. 109.—Recoil System, Dependent Type, with Floating Piston.

The upper cylindrical hole contains the piston and piston rod, the latter being fastened to the gun lug. The space in front of the piston is filled with air at atmospheric pressure, drawn through the respirator vent. The space in rear of the piston is filled with oil and communicates with the lower cylinder by a large port.

The lower or recuperator cylinder contains the oil gage, the regulator, diaphragm, spring, floating piston, and the nitrogen filling valve.

The *regulator* is screwed in the breech end of the recuperator cylinder. It is a hollow steel forging, the central portion being of much smaller diameter than the two ends which fit into the recuperator cylinder. The front end of the regulator terminates in a *choke ring* through which passes a hollow throttling bar attached to the diaphragm. In the front part of the regulator are carried four one-way spring valves which open into an orifice formed by the clearance between the choke ring and the exterior surface of the throttling bar. Vents in the rear of the regulator permit the free passage of oil on the outside and inside of the regulator cylinder. The inner surface of the regulator cylinder contains two throttling grooves of varying depth.

The *floating piston* is located just forward of the regulator. The space in front of the piston contains compressed nitrogen for recupera-

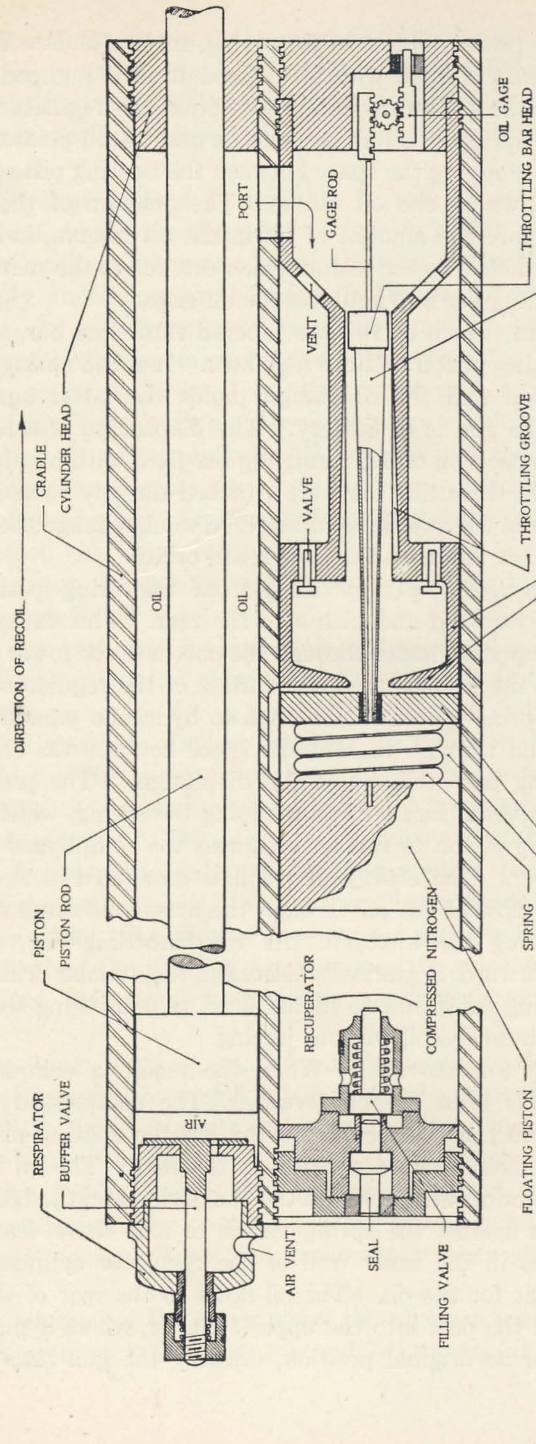


FIG. 110.—Recoil System (Puteaux) for 75-mm. Field Gun Model 1897 (French.)

tion at an initial pressure of 1775 lb. per sq. in. at 70° F. The space in rear of the piston is filled with oil. Enough oil is pumped into the cylinder to force the piston forward, away from the regulator, so that it floats between the gas pressure on one side and the oil pressure on the other. The oil occupying the space between the floating piston and the diaphragm is known as the *oil reserve.* The position of the floating piston, and therefore the amount of oil in the oil reserve, is indicated by a small rod attached to the piston which extends to the rear through the hollow throttling bar and actuates the oil gage.

The diaphragm, which carries the tapered throttling bar, is located between the floating piston and the regulator. A coiled spring between the floating piston and the diaphragm holds the latter against the regulator when the gun is in battery. The diaphragm is necessary in order to keep the position of the throttling bar fixed with relation to the choke ring. If the throttling bar were attached directly to the floating piston, variations in the amount of oil reserve would change the position of the throttling bar and thus vary the recoil orifice.

Action during Recoil.—In recoiling from the firing position the gun draws the piston rod and piston to the rear. This causes the oil to flow from the upper cylinder through the port into the lower cylinder. It passes through the vents to the outer surface of the regulator cylinder to the one-way spring valves, which open to hydraulic pressure in this direction only, and through the annular space between the choke ring and the throttling bar attached to the diaphragm. The pressure on the diaphragm drives it forward, compressing the spring, which in turn moves the floating piston to further compress the compressed nitrogen in the recuperator. The energy of recoil is dissipated in overcoming the resistance to flow of the oil through the numerous small openings, and in compressing the nitrogen. As the throttling bar, which is tapered, moves forward, it gradually decreases the annular orifice at the choke ring, offering resistance to the oil flow, thus bringing the gun to its position of extreme recoil without jarring.

Action during Counter-recoil.—When the recoil is completed the floating piston has been pushed forward. The compressed nitrogen (3400 lb. per sq. in.) of the recuperator pushes the floating piston and diaphragm from their forward position to the rear. The oil is forced through the annular opening between the choke ring and the hollow rod. The oil now acts against the spring valves to seat them, leaving the throttling grooves in the inner wall of the regulator cylinder as the only means of exit for the oil. The oil flows to the rear of the lower cylinder, through the port into the upper cylinder, where it pushes the piston forward to its original position, drawing the gun into battery.

The throttling grooves of the regulator cylinder are so designed that the orifice is gradually diminished to zero as the diaphragm and throttling bar move to the rear. This arrangement and friction of packing results in a counter-recoil movement which returns the gun "in battery" without jarring.

Counter-recoil Buffer.—In addition to the friction of the packing, two different means are provided to furnish buffer action at the end of counter-recoil. In the first place, the area of the throttling grooves is gradually diminished as the head on the end of the throttling bar approaches its in-battery position. This condition causes the gun to come to rest slowly in its counter-recoil movement.

Buffer action is assisted by the *respirator*, or Schindler buffer. This is a device containing a one-way air valve which is screwed into the front end of the upper cylinder. During recoil, the rearward movement of the piston causes the air to be drawn in from the outside, the buffer valve opening to pressure from that direction only. During counter-recoil the valve is closed. The air, now compressed by the returning piston, escapes through an orifice and acts as a buffer near the end of counter-recoil.

The valve plate and its seat contain three small ports each. If the return in battery is too slow when the valve is fully closed, one or more of the ports are set to remain open during counter-recoil. The effective resistance to counter-recoil by the buffer is thus reduced.

Oil Gage.—The recuperator has practically no nitrogen leakage; consequently the pressure changes only with a variation of the volume of oil in the cylinder. The oil gage, at the rear end of the lower cylinder, indicates the amount of oil in the oil reserve when the gun is at rest.

In case of oil leakage, the floating piston tends to get near the diaphragm under the action of the nitrogen pressure in the recuperator, the small rod of the floating piston pushes the upper rack of the gage, and, through the action of the pinion, the lower rack recedes into the cylinder.

If the liquid is in excess, the reserve increases, the floating piston is pushed forward, the small rod moves from contact with the upper rack, and the liquid pressure acting on the lower rack causes the gage to protrude from the cylinder.

Nitrogen Filling Valve.—The nitrogen valve in the front head of the recuperator cylinder provides a means for safely releasing the highly compressed nitrogen from the recuperator when disassembly is required.

After removal of the cover plate, the nitrogen seal and its packing are unscrewed and removed. A rod of smaller diameter is intro-

duced in the central hole, slightly raising the valve from its seat, permitting the nitrogen to escape slowly.

After assembly of the recuperator, the compressed nitrogen is forced in by a pump, the one-way nitrogen valve opening to pressure from that direction only. When the required pressure has been built up, the seal is replaced.

A similar mechanism provides a means for replenishing the oil supply.

216. French 155-mm. Howitzer Recoil System (Schneider).—The recoil system of the French 155-mm. Howitzer, Model 1918 (Schneider), is the hydropneumatic type, consisting of an independent brake and recuperator with oil in direct contact with compressed nitrogen. The schematic drawing, Fig. 111, shows the relative location of the recoil brake, recuperator, and buffer.*

Action during Recoil.—As the gun recoils, the recuperator cylinder is drawn to the rear. The piston, fastened to the cradle, remains stationary, forcing the oil to rush into the nitrogen tank, compressing the nitrogen.

The recoil cylinder also moves with the gun, sliding over the hollow piston rod. The tapered buffer rod, fastened to the gun lug, slides into and out of the hollow piston rod.

The oil in the front part of the recoil cylinder flows through the vents in the rear end of the hollow piston rod into the rear part of the recoil cylinder, passing through the annular aperture between the throttling ring and the tapered buffer rod. At the beginning of recoil this aperture is large. As recoil progresses, the orifice diminishes until it is zero. This method is known as central throttling. During recoil, oil is forced into the *forward* end of the hollow piston rod, passing between the inner surface of this rod and the enlarged end of the buffer rod, thence through ports in the counter-recoil check valve which remain open. The passage of the oil through these various small openings results in the braking of recoil.

Action during Counter-recoil.—After recoil ceases, the compressed nitrogen in the recuperator expands, forcing the oil against the piston in the middle cylinder, causing the howitzer to be returned to the firing position.

The flow of oil in the recoil cylinder, now reversed, firmly seats the counter-recoil check valve against the forward end of the buffer rod. The liquid in the forward end of the piston rod, now flowing to the rear, must go between the outer surface of the valve and the inside of the hollow rod. The bore of the hollow rod is slightly conical at the

* Compressed nitrogen is used in the recuperator instead of air as shown in Fig. 111.

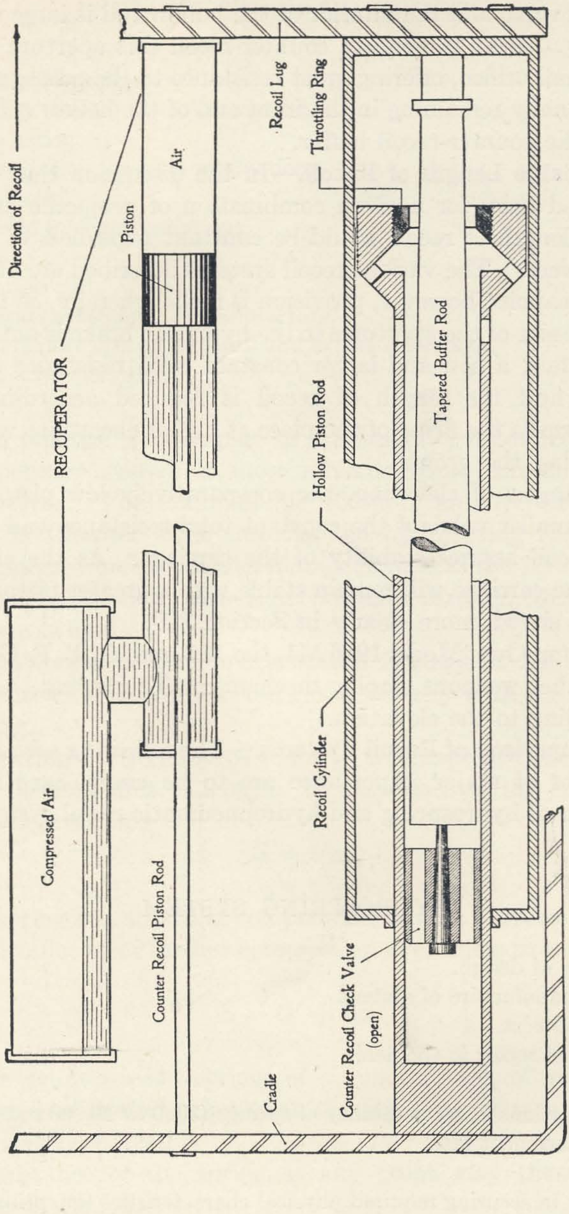


FIG. 111.—Recoil System (Schneider) for 155-mm. Howitzer, Model 1918 (French).

front end. At the beginning of counter-recoil, the annular space between the valve and the interior of the hollow rod is large and the oil passes freely. Near the end of counter-recoil this aperture diminishes to a very small orifice, offering great resistance to the passage of the oil. The liquid finally remaining in the front end of the hollow rod then acts as a hydraulic counter-recoil buffer.

217. Variable Length of Recoil.—In the discussion thus far, it has been assumed that, for a given combination of projectile and powder charge, the length of recoil would be constant regardless of the elevation of the piece. The various recoil systems described are of this type. In certain weapons, however, provision is made whereby, as the piece is elevated, the size of the apertures in the hydraulic brake is automatically reduced. Thus, a new and larger constant total resistance to recoil is introduced, and the length of recoil is reduced accordingly. This provision permits the firing of the piece at higher elevations without the breech striking the ground.

At low angles of elevation, the comparatively low piston-rod pull due to the smaller value of the constant total resistance and the longer length of recoil assures stability of the carriage. As the elevation is increased, the carriage will remain stable with a greater piston-rod pull. This will be shown more clearly in Section 229.

The 75-mm. Gun, Model 1916 M1, the 155-mm. G. P. F. Gun, Model 1918, and other weapons employ mechanisms for varying the length of recoil according to the elevation.

218. Comparison of Recoil Systems.—The following advantages and disadvantages of major importance are to be emphasized in making a comparison of hydrospring and hydropneumatic recoil systems.

HYDROSPRING SYSTEM

Advantages:

Simplicity of design.
Ease of manufacture of system.
Low initial cost.
Rapidity of repair in the field.

Disadvantages:

Wide variations in serviceability of springs (3000 to 10,000 rounds).
High replacement rate.
Bulkiness.
Difficulty in securing required physical characteristics for springs.
Weight prohibitive for large-caliber mobile matériel.
(Disadvantages increase with increase in caliber.)

HYDROPNEUMATIC SYSTEM

Advantages:

Reliability of performance.
Durability (20,000 to 40,000 rounds).
Smooth action.
Standardization for mass production.
Compactness.
Adjustable to slight variations.

Disadvantages:

High initial cost.
Specialization required in manufacture.
Repairs require special facilities and expert mechanics.
Maintenance in storage.

Modern practice is to employ in the design of a particular gun and mount whichever system is most advantageous, considering all the factors involved. For example, the 105-mm. antiaircraft gun mount illustrated in Chapter VIII employs the hydrospring type with two spring-cylinders, whereas on such mobile mounts as the 75-mm. howitzer carriage and the 155-mm. gun—8 in. howitzer carriage, the hydropneumatic system is used.

219. Resistance of the Counter-recoil Springs or Air Cylinders.—The resistance S of a coiled spring varies directly with the compression of the spring.

Representing by G the force required to compress the spring, when free, over the first unit of length, the resistance of the spring at any length of compression x is

$$S = Gx$$

If the spring has an initial compression so that it exerts a resistance G', the resistance after further compression over a length x becomes

$$S = G' + Gx \tag{20}$$

For the counter-recoil springs of a gun carriage, G' represents the residual pressure in the spring when the gun is in battery and x represents any length of recoil.

The resistance of the spring at any point may therefore be determined from Eq. (20).

Air compressed by a piston in a cylinder acts as a spring and follows the law given by Eq. (20). When an air cylinder is used, S becomes the total pressure of the air over the effective area of the air piston.

220. Total Resistance to Recoil.—The total resistance to recoil is composed of the resistance offered by the brake, the resistance produced by friction, the resistance (either plus or minus) caused by the inclination of the top of the chassis or the recoil slides, and the resistance produced by the counter-recoil springs or air cylinders.

Let W be the weight of the moving parts.

M, the mass of the moving parts.

f, the coefficient of friction.

α, the angle of inclination of the chassis rails or of the recoil slides.

S, the resistance of the springs or air cylinders at any point of recoil.

P, the total resistance of the hydraulic brake or the total hydraulic pressure on the piston, at the same point of recoil.

R, the total resistance to recoil.

The resistance produced by friction is $fW \cos \alpha$; that caused by inclination of the chassis rails or the recoil slides is $W \sin \alpha$. The sign of $\sin \alpha$ may be either plus or minus. It is *plus* only when the center of gravity of the recoiling parts is lifted during recoil. In the formulas given below it is taken as *minus*, which is the case when the center of gravity is lowered during recoil. The total resistance at the point of recoil considered is therefore

$$R = W(-\sin \alpha + f \cos \alpha) + S + P \tag{21}$$

Resistance of the Hydraulic Brake—Pressure in the Cylinder.—The hydraulic pressure on the piston of the brake cylinder at any point of recoil may now be determined from Eq. (21) by substituting for R its constant value from Eq. (17); for S, its value for any point from Eq. (20); and for $W(-\sin \alpha + f \cos \alpha)$, its constant value. Thus,

$$P = R - W(-\sin \alpha + f \cos \alpha) - S \tag{22}$$

221. Relation between Pressure, Area of Orifice, and Velocity of Recoil.—In this discussion the term *aperture* will denote the cut through the piston, and the term *orifice* that portion of the aperture open to the flow of the liquid; and we will consider for simplicity that there is but one aperture and one orifice.

Let A be the *effective* area of the piston in square feet, that is, the area of the piston minus the area of the piston rod and aperture. The square foot is taken as the unit of area because in the velocities involved in the discussion the foot is the unit of length.

Let a be the area of orifice at any point of recoil.

v_r, the velocity of retarded recoil at the point considered.

v_l, the velocity of the liquid through the orifice at the point considered.

γ, the weight of a cubic foot of the liquid.

P, the total pressure on the piston at the point considered.

The cylinder being full of liquid, the volume that passes through the orifice is the volume displaced by the piston. Therefore at any instant

$$v_rA = v_la$$

or, for the velocity of flow,

$$v_l = \frac{v_rA}{a} \tag{23}$$

From Torricelli's law for the flow of liquids through orifices, the pressure required to produce this velocity of flow is the pressure due to a column of liquid whose height h is given by the equation

$$v^2 = 2gh \tag{24}$$

Substituting for v the value of v_l from Eq. (23) and solving for h,

$$h = \frac{v_r^2A^2}{2ga^2} \tag{25}$$

The weight of a cubic foot of the liquid being γ, the weight of the column whose area of cross section is unity will be γh, and the weight of the column whose area of section is equal to that of the piston will be $A\gamma h$. $A\gamma h$ is therefore the total pressure on the piston, and, substituting in this expression the value of h from Eq. (25), the total pressure on the piston for any velocity v_r is

$$P = \frac{\gamma A^3v_r^2}{2ga^2} \tag{26}$$

This equation is general and expresses the relation that exists between P, A, and a for any given velocity of recoil.

Solving for a^2,

$$a^2 = \frac{\gamma A^3v_r^2}{2gP} \tag{27}$$

222. Area of Orifice.—With the relations established in Eqs. (20), (22), and (27), which are repeated here, and the curve v_{rx} in Fig. 105, the

variable area of orifice in the piston can now be determined, the total resistance to recoil being constant throughout.

$$S = G' + Gx \tag{20}$$

$$P = R - W(-\sin\alpha + f\cos\alpha) - S \tag{22}$$

$$a^2 = \frac{\gamma A^3 v_r^2}{2gP} \tag{27}$$

The dimensions of the recoil cylinder will be fixed within narrow limits by the design of the carriage, and by the requirement that the pressure per unit of area must not be so great as to render difficult the effective packing of the stuffing boxes through which the piston rod passes. We will therefore assume that the diameters of the cylinder and piston rod are given, and as the relation between the total area of piston and the effective area may be readily established we will assume that the effective area A of the piston is known.

Brake with Variable Hydraulic Pressure.—The value of P at any point in the cylinder, for which the length of recoil is x, is obtained from Eq. (22), the proper value of S for the point having been first determined from Eq. (20). The value of v_r is taken from the curve v_{rx} in Fig. 105 at the ordinate whose abscissa is x. The values of P and v_r thus determined are substituted in Eq. (27). The resulting value of a is the area of orifice at the given point.

Constant Hydraulic Pressure.—If P in Eqs. (26) and (27) is constant, the velocity of recoil and the area of orifice when the powder gases cease to act may be found by substituting v_{r_τ} for v_r and a_0 for a; thus

$$a_0^2 = \frac{\gamma A^3 v_{r_\tau}^2}{2gP} \tag{28}$$

Combining Eqs. (27) and (28) gives, for any given cylinder,

$$\frac{a}{a_0} = \frac{v_r}{v_{r_\tau}} \tag{29}$$

from which it is evident that, in order to maintain a constant hydraulic pressure in the cylinder, the area of the orifice must vary directly with the velocity of recoil.

Substituting in Eq. (29) the value of v_r/v_{r_τ} obtained by combining Eqs. (16) and (18),

$$a = a_0\sqrt{\frac{L - x}{L - E_{r_\tau}}} \tag{30}$$

that is, with constant pressure in the cylinder, the area of orifice varies as the ordinates of a parabola.

Eq. (30) refers only to that part of the recoil *after the powder gases cease to act.*

223. Brake with Constant Pressure.—When there are no springs and no other variable resistance is found in the recoil system, S becomes 0 in the value of P, Eq. (22), and a constant pressure will be required in the brake.

The area of orifice for this condition is determined from

$$P = R - W(-\sin\alpha + f\cos\alpha)$$

$$a_0^2 = \frac{\gamma A^3 v_{r_\tau}{}^2}{2gP} \tag{28}$$

$$\frac{a}{a_0} = \frac{v_r}{v_{r_\tau}} \tag{29}$$

Find the value of P from the first equation in the manner already explained. v_{r_τ} and A are known and a_0 may now be determined from Eq. (28). The area of orifice at any other points may now be obtained by means of Eq. (29), using the values of v_r taken from the curve v_{rx}. The areas of orifice from the point E_{r_τ} to the end of recoil may be obtained from Eq. (30).

Horizontal Chassis.—If the chassis rails are horizontal and the top carriage is mounted on rollers, so that we may neglect the friction, the term $W(-\sin\alpha + f\cos\alpha)$ in the value of P, Eq. (22), also becomes zero, and P reduces to R. Substituting for R in Eq. (16) the value of P from Eq. (28) and solving for a_0, we obtain

$$a_0^2 = \frac{\gamma A^3}{W}(L - E_{r_\tau}) \tag{31}$$

Under these conditions, a_0 is independent of the velocity of recoil and is dependent only on the remaining length of recoil after the powder gases cease to act. Therefore, for a given area of orifice at E_{r_τ}, the remaining length of recoil will be the same no matter what the initial velocity of the projectile, the charge of powder, or the angle of fire may be.

The brake, therefore, requires no adjustment for varying conditions of fire, and in this respect it possesses further advantage over the brake with constant orifices and variable pressure.

The explanation of the independence, under the given conditions,

of the remaining length of recoil and the velocity will appear by substituting P for R in Eq. (16), which gives

$$(L - E_{r_r}) = \frac{Mv_{r_r}^2}{2P} \tag{32}$$

In Eq. (28) we see that for a given value of a_0 the pressure P must vary directly as $v_{r_r}^2$. Therefore, in Eq. (32), as P varies with $v_{r_r}^2$, $L - E_{r_r}$ will remain constant.

224. Profile of the Throttling Bar.—Suppose there are n similar apertures cut in the piston. The area of each orifice at any point in the cylinder will then be a/n, a being determined for the particular point from Eq. (27). Let b, Fig. 112, be the depth and d the width of each aperture. The throttling bar has a variable depth y and a constant thickness which is equal to the width of the aperture d.

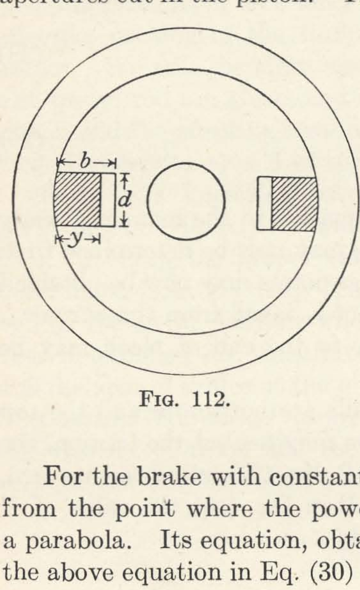


FIG. 112.

Then for the area of each orifice at the given point in the cylinder we have

$$\frac{a}{n} = d(b - y)$$

For the brake with constant pressure the profile of the throttling bar from the point where the powder gases cease to act to the end will be a parabola. Its equation, obtained by substituting the value of a from the above equation in Eq. (30) and reducing, is

$$y = b - \frac{a_0}{nd}\sqrt{\frac{L - x}{L - E_{r_r}}} \tag{33}$$

Neglected Resistances.—In the foregoing discussion we have neglected the resistance produced by the friction of the liquid and the contraction of the liquid vein. It has been found by experiment that the error due to the neglect of these resistances may be corrected by assigning to v_l, the velocity of the flow through the orifices, Eq. (23), a value greater than the actual value as expressed in Eq. (24). The value to be substituted is determined by experiment for each class of carriage and takes the form $v_s = av_l + b$, a and b being constants. The result of the

substitution is an increase in the area of orifice for any given pressure in the cylinder, the value of a given in Eq. (27) being too small.

PROBLEMS

1. The field gun referred to in Problems 1 to 3, Section 211, is fired horizontally. The resistance of the counter-recoil springs at the time the powder gases cease to act is 800 lb. The coefficient of friction on the recoil slides is 0.1. The oil in the recoil cylinder weighs 50 lb. per cu. ft. The effective area of cross section of the hydraulic cylinder is 3.32 sq. in.

Determine the area of orifice at the time the powder gases cease to act under the assumption that the total resistance to recoil is constant, and the total length of recoil is 45 in.

2. From the data obtained in preceding problems, plot the curve showing area of orifice as a function of distance recoiled. Assume the initial resistance of the counter-recoil springs to be 600 lb.

225. Length of Recoil in Artillery of Position.—In artillery of position the gun carriage is rigidly bolted to a fixed platform. Its mechanism is such as to allow the gun and the attached parts to recoil on firing. The hydraulic brake cylinder and its piston are attached, respectively, to the moving and fixed parts of the carriage, or vice versa, in such a way as to cause the piston to be drawn through the cylinder as the gun recoils.

When constant total resistance is to be exerted by the recoil system, which is always the case in artillery of position, either the total resistance or the length of recoil may be assumed and the other determined from Eq. (17). The assumption of a very long recoil would reduce the resistance and consequently the strain on the carriage and permit its parts to be made lighter. However, the necessary increase in the length of the recoil slides might overbalance the saving and add to the cost of the carriage.

In those carriages, such as mortar carriages, antiaircraft gun carriages, and barbette carriages, which permit the firing of the gun at high angles of elevation, a very long recoil cannot be used without employing base rings and racers of great diameter. Various questions of design indicated the advisability of adopting a recoil of about 42 in. for the gun on the 16-in. barbette carriage and of 48 in. for the gun on the 14-in. turret mount.

In disappearing carriages, the length of the recoil is determined more by the necessity of giving the gun the proper movement in recoil than by limitation of the strains brought upon the carriage.

With the exception of the disappearing carriage, the recoil for artillery of position is comparatively short, considering the very large recoil forces involved. The following table gives the length of recoil, in inches,

measured along the recoil cylinder, for certain guns mounted on the carriages indicated:

		Length of Recoil, In.
15-pdr. Pedestal mount	Model 1903	9
6-in. Pedestal mount	Model 1900	15
12-in. Mortar	Model 1896	24
12-in. Mortar	Model 1908	24
12-in. Barbette	Model 1917	30
14-in. Turret	Model 1909	48
14-in. Railway	Model 1920	35
16-in. Barbette	Model 1919	42

226. Horizontal Recoil System on Seacoast Carriages.—Figure 113 will serve to illustrate the general arrangement of the recoil system installed on the seacoast disappearing carriages. In this figure the mechanism is shown in partial recoil.

The two hydraulic recoil cylinders c are integral parts of the top carriage and move to the rear when the gun is fired. The piston rods are attached to the chassis and remain fixed and stationary in position. These rods enter the cylinders through stuffing boxes designed to prevent the escape of oil. The bearings for the gun lever trunnions of the disappearing carriages are in the same casting with, and above, the recoil cylinders. On discharge of the piece, the movement of the recoil cylinders to the rear forces the liquid in the cylinders through the orifices in the stationary pistons.

The direction of the movement of the cylinders during recoil is toward the top of the page as shown in the larger section of Fig. 113.

To equalize the pressure in the two cylinders, their interiors are connected at the front by the pipe a and at the rear by the two pipes d and f. Each half of the pipes d and f has unobstructed communication with the other half of the same pipe through a valve box v. A cross pipe b connects the pipe a with the valve box. A path is afforded through the pipes a, b, d, and f for the flow of oil from one side of the piston to the other, which path, as well as the orifices in the pistons, must be considered in determining the area of orifice.

The area of orifice, and consequently the length of recoil, is calculated for standard conditions of loading. Any variation in these conditions will vary the length of recoil, and thus vary the height of the breech of the gun above the loading platform. Standard conditions of loading do not always exist, and the resistance in the cylinders will vary with the viscosity of the oil which itself varies with the temperature. It is desirable, therefore, to have means for varying the resistance

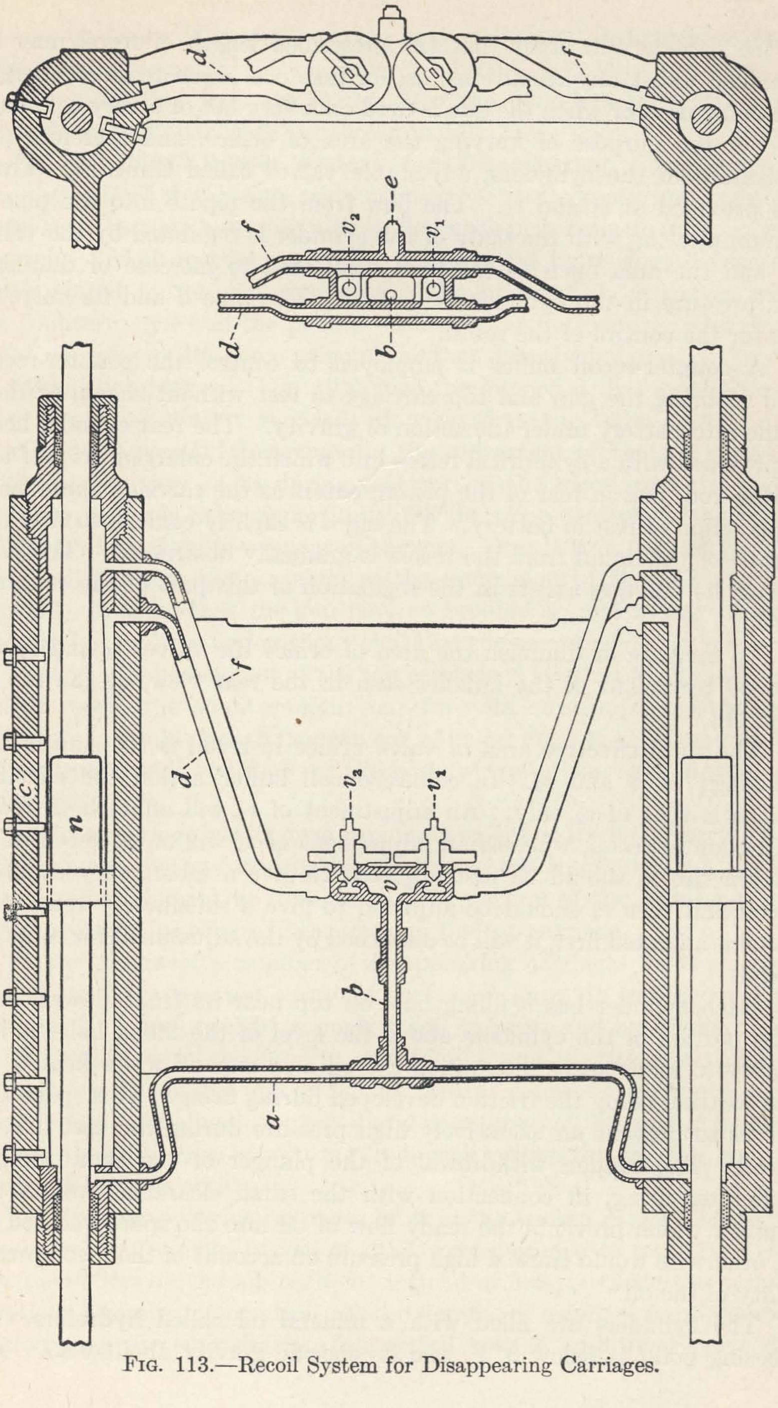


FIG. 113.—Recoil System for Disappearing Carriages.

in the cylinders in order that the prescribed length of recoil may be obtained under any conditions, as, for instance, when reduced charges are being used or when the gun is fired on a very hot or a very cold day.

For the purpose of varying the area of orifice, and therefore the resistance in the cylinders, adjustable valves called throttling valves are provided at v_1 and v_2. The flow from the pipe b into the pipe d communicating with the body of the cylinder is regulated by the valve v_1, and the area open to the flow is affected to increase or diminish the pressure in the cylinder as desired. The pipe d and its valve v_1 are for the control of the recoil.

A counter-recoil buffer is employed to control the counter-recoil and to bring the gun and top carriage to rest without shock, as they come into battery under the action of gravity. The rear cylinder head is provided with a cylindrical recess into which the enlargement n of the piston rod, just in rear of the piston, enters as the carriage approaches its position of rest in battery. The lug n is slightly conical, so that the escape of the liquid from the recess is gradually obstructed. The pipe f with its valve v_2 assists in the regulation of this part of the counter-recoil.

To increase or diminish the area of orifice the valves v_1 and v_2 are moved by means of the handles seen in the rear view, at the top of Fig. 113.

The total effective area of valve orifice in recoil is the sum of the openings of v_1 and v_2. In counter-recoil buffer action the effective orifice is that of v_2 only. An adjustment of v_2 will affect both recoil and counter-recoil, whereas an adjustment of v_1 will affect recoil only. In practice v_2 should be first adjusted to give a satisfactory counter-recoil and then v_1 should be adjusted to give a satisfactory recoil. If recoil is adjusted first, it will be disturbed by the adjustment for counter-recoil.

Each cylinder has a filling hole on top near its front (lower) end. The portion of the cylinders above the level of the filling holes is left empty to allow space into which the oil may expand when heated by the weather or by the friction developed during firing. This space also serves to prevent an excessively high pressure during the first part of recoil. The sudden withdrawal of the plunger of the counter-recoil buffer on firing, in connection with the small clearance around the plunger which prevents the ready flow of oil into the space vacated by it, otherwise would cause a high pressure on account of the incompressibility of the oil.

The cylinders are filled with a mineral oil called hydroline. Its freezing point is below 0° F. and its specific gravity about 0.85. The

oil may be drawn off through a hole *e* in the valve box, ordinarily stopped with a screw plug.

The throttling bars are fastened to the cylinders by screw bolts through the cylinder walls, as shown in Fig. 113.

227. Modified Recoil System for Disappearing Carriages.—In some models of the disappearing carriage, separate recoil and counter-recoil systems have been provided so that each may have an independent control. Recoil on these carriages is controlled by a single hydraulic brake placed in the counterweight. The brake cylinder moves with the counterweight and the piston rod is fixed at both ends. The recoil brake operates on the same principle as that described above.

It will be observed (Fig. 121) that the gun on a disappearing carriage is moving almost vertically downward in the latter part of the movement in recoil. Consequently the movement of the top carriage to the rear is very slight during this part of the recoil, and the slight movement affords little opportunity for the close control by the recoil cylinders of the final movement of the gun. But it is in the last part of the recoil that complete control of the movement of the gun is most desirable, in order that the gun may be brought to rest at any desired position for loading, and without shock to the carriage.

Whereas the movement of the top carriage is least rapid at the latter end of recoil, the counterweight has then its most rapid movement. Therefore it would appear that a recoil cylinder fixed so as to move with the counterweight would afford the best control of the final movement of the gun.

The top carriage has its most rapid movement at the latter part of the movement of the gun into battery, whereas the counterweight has its least rapid movement at that time. The control of the counter-recoil therefore might be effected best through the top carriage.

In the design of a number of disappearing carriages for 6-in. guns and all the disappearing carriages for 14-in. guns, it was decided to place in the counterweight a single recoil cylinder and hydraulic brake which would control recoil only; and to add, on the chassis, a separate counter-recoil cylinder and brake to control counter-recoil only. By these means, adjustment for recoil and counter-recoil became independent and the advantage of securing from each system the greatest control of movement was obtained.

The last disappearing carriages built in the United States, the 16-in. Disappearing Carriage, Model of 1917, were designed to retain the two recoil cylinders on the top carriage, instead of incorporating the system mentioned above. Operation of the modified recoil system demonstrated that the complication introduced by the additional parts did

not have corresponding advantages in actual operation, and the general plan of recoil system for the newer carriage reverted to the earlier and simpler design.

228. Determination of Length of Recoil of Guns Mounted on Wheeled Carriages.—The construction of all modern wheeled carriages is such as to allow the gun to recoil in the direction of its axis. The resistance to recoil developed by the recoil system pulls forward on the gun and backward on the carriage, tending to move the latter to the rear. Actual motion of the carriage to the rear is prevented by a spade sunk in the ground at the end of the trail of the carriage and so constructed as to present a broad surface to the ground in rear. Under ordinary conditions the ground will resist a pressure of 80 lb. per sq. in. of spade surface, and knowing the pressure developed by the pull on the piston rod, which is the only force acting on the carriage, the size of spade can be determined.

Another effect produced by the resistance to recoil is a tendency to rotate the carriage around the point of support of the trail or to cause

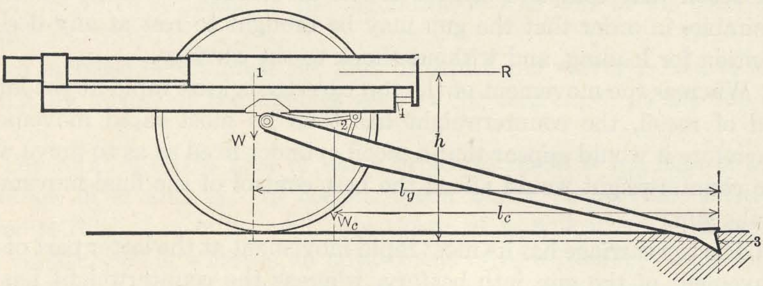


FIG. 114.

the wheels to jump from the ground. Such a movement is very undesirable, as it interferes with rapid aiming and firing of the piece. To prevent this rotation or jump, the moment of the weight of the gun and carriage taken with respect to the point of support of the trail must be greater than the moment of the resistance to recoil taken with respect to the same point. This is the principal consideration which determines the total resistance of the recoil systems used in wheeled carriages.

229. Limiting Value of Total Resistance to Recoil in Wheeled Carriages.—In order to determine the limiting value of the total resistance to recoil in a wheeled carriage, assume the gun in a horizontal position and on level ground, as shown diagrammatically in Fig. 114.

Let W be the weight of the recoiling parts acting at their center of gravity 1.

W_c, the weight of the fixed parts of the carriage acting at their center of gravity 2.

R, the total resistance to recoil.

l_g, the lever arm, when the gun is in the firing position, of the weight W, with respect to the center of pressure of the trail spade assumed some distance under the ground at 3.

l_c, the lever arm of the weight W_c fixed with respect to the same point.

h, the height of the center of gravity of the gun above the same point.

x, the distance recoiled at any time.

The force R in reality acts on the carriage along the line of the piston rod 4. Since, however, the gun is constrained by the cradle to move straight to the rear, without rotation, the moment of this force with respect to the point of support of the trail is the same as that of an equal and parallel force passing through the center of gravity of the gun as represented at R.

The value of R that will just fail to cause the wheels to rise from the ground when the gun is in the firing position is obtained by equating moments, or representing this value of R by R_m,

$$R_m h = W l_g + W_c l_c$$

or,

$$R_m = \frac{W l_g + W_c l_c}{h} \tag{34}$$

When the gun has recoiled a distance x, the lever arm of W becomes $l_g - x$, and

$$R_m = \frac{W(l_g - x) + W_c l_c}{h} \tag{35}$$

This is evidently a smaller value than that given by Eq. (34) and shows that a value of R small enough to prevent jump of the wheels in the early part of the recoil might still cause jump toward the end of the recoil as the moment of the weight of the recoiling parts becomes less.

In Fig. 115 the line $R_m R_m$ indicates the maximum permissible values of R obtained from Eq. (35) and plotted as a function of the length of recoil for a gun like that shown in Fig. 114.

If we assume a constant value of R represented by R_c, we can calculate the corresponding length of recoil L_c by Eq. (17). If there is to be no jump, the value of R_c must be so selected that the rectangle OR_c, the

area of which represents the work done by the system in bringing the recoiling parts to rest, will lie entirely beneath the line R_mR_m. Accordingly, with a constant total resistance, the length of recoil cannot be shortened beyond a certain limit if stability is to be maintained.

The length of recoil can be further shortened, however, and stability maintained, if the total resistance during recoil is made to decrease instead of remaining constant, and if proper values are selected for the total resistance at each point. For example, if the total resistance

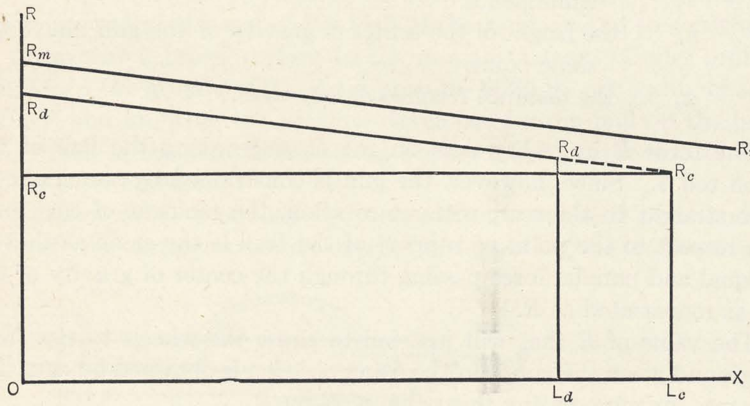


FIG. 115.

is made to vary as indicated by the line R_dR_d, at the same rate as R_mR_m, the length of recoil could be reduced to L_d. The ratio $\frac{R_m}{R_d}$ is the factor of stability of the carriage.

If the length of recoil is such that the carriage is stable in firings at zero degrees elevation, it will be stable at all higher elevations. This is evident from consideration of Fig. 114, assuming the gun to be elevated and the action line of R correspondingly changed. Advantage is taken of this greater stability at high elevations, by provision of means whereby the length of recoil is automatically reduced as the piece is elevated, as previously discussed in Section 217.

PROBLEMS

1. A certain field gun with its recoiling parts weighs 950 lb. Its center of gravity, with the gun horizontal and on level ground, is 40.5 in. above and 115 in. forward of the point of support of the spade. The carriage weighs 1610 lb. and its center of gravity is 98 in. forward of the same point.

What are the maximum values the resistance to recoil can have, without causing jump of the wheels, both when the gun is in the firing position and when it has recoiled 45 in.?

2. The 6-in. howitzer with its recoiling parts weighs 2150 lb. Its center of gravity when horizontal and in the firing position is 43 in. above and 157 in. forward of the point of support of the spade. The weight of the non-recoiling parts of the carriage is 5115 lb., and the center of gravity is 112 in. forward of the point of support of the spade.

Determine the maximum value the resistance to recoil can have to insure stability of the carriage when firing horizontally, both when the gun is in battery and when it has recoiled 63 in.

230. Initial Strength of Counter-recoil Springs or Air Cylinders.—The initial strength of the counter-recoil spring columns or air cylinders is the force which they exert against the gun in the firing position. This force must be great enough to hold the gun in that position at the highest angle of elevation at which it is to be used as well as to overcome the friction on the recoil slides as the gun runs forward to the firing position.

Let W be the weight of the gun and recoiling parts;

ϕ, the angle of elevation;

f, the coefficient of friction;

G', the initial strength of the counter-recoil springs or air cylinders.

The weight to be lifted is $W \sin \phi$.

The friction to be overcome is $fW \cos \phi$.

We therefore have

$$G' = W \sin \phi + fW \cos \phi \qquad (36)$$

If the initial strength of the springs, the required movement, and the coefficient of friction are known, springs may be designed to comply with these conditions.

If air cylinders are used, the pressure G' is the total air pressure over the effective area of the air piston. The volume of the air reservoir is made large enough so that when reduced by the stroke of the piston in recoil, the pressure at the end of recoil will not be more than about twice the initial pressure. The pressure per square inch in air cylinders is made as low as practicable, to prevent undue leakage.

PROBLEMS

1. Determine the required initial strength of the counter-recoil springs of the field gun referred to in Problem 1, Section 229, under the assumption that the gun is to be at 20 degrees elevation. Take coefficient of friction 0.25.

2. Determine the required initial strength of counter-recoil springs in the 6-in. howitzer referred to in Problem 2, Section 229, to permit firing at 40 degrees elevation. Coefficient of friction 0.25.

231. Equilibrators.—Modern mobile artillery carriages are so designed as to permit firings at high angles of elevation. To afford the

requisite stability at low firing angles, the center of mass of the gun and other recoiling parts must be kept as low as possible. This, however, necessitates provision of means whereby the breech can be prevented from striking the ground during recoil in firing at high elevations.

The use of the variable length of recoil, previously discussed, is a partial solution only. Except at fairly low elevations (e.g., under 20° in the 155-mm. G. P. F. gun), it was necessary to provide also a recoil pit dug in the ground. This increases the time and effort required to emplace the weapon for firing, and reduces the rate of fire because of loading difficulties. In modern designs of weapons, the solution has been to move the gun forward relative to its carriage, locating the trunnions of the tipping parts (those that move together as the piece is elevated) closer to the breech of the gun and considerably in rear of the center of mass of these parts. This creates a condition of muzzle preponderance which must be equalized; otherwise, there will be undue strain on the elevating mechanism and difficulty in elevating the piece. Certain recent types of fixed and railway artillery employ a counterweight on the breech end of the gun, the result being to move the center of mass of the tipping parts to a point at or near the trunnions and to equalize the torque at the trunnions. The weight increase involved, however, is objectionable in mobile artillery..

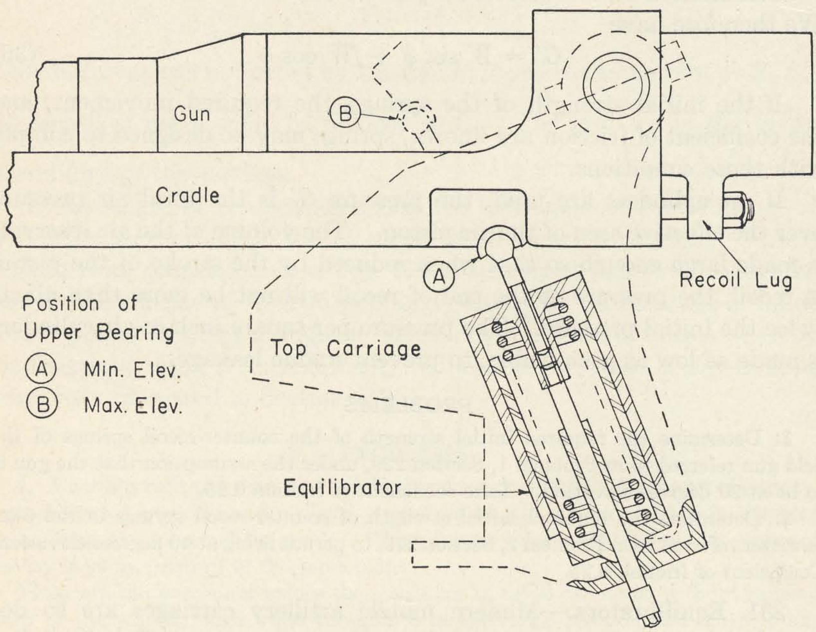


FIG. 116.—Equilibrator on 75-mm. Gun Mount M2.

Devices known as *equilibrators* are employed in the latest types of mobile weapons. They are shown on the 75-mm. Gun Carriage, M2, the 75-mm. Howitzer Carriage, M3, and other new weapons illustrated in Chapter VIII. The equilibrator exerts a force on the tipping parts which tends to elevate the piece, the torque being equal and opposite to that produced by the unbalanced weight forward of the trunnions. There are two types of equilibrators, spring actuated and pneumatic, employing either compressed springs or compressed gas (usually nitrogen) to exert the balancing force required at various elevations of the gun.

One type of spring equilibrator is illustrated in Fig. 116. Units are provided on each side of the carriage. The mechanism consists of two telescoping sleeves forming a housing for a helical spring, which is always under compression, and a central guide rod. The force of the spring is exerted downward against a non-tipping part of the mount, the top carriage, and upward against the tipping parts which are trunnioned in the top carriage as shown.

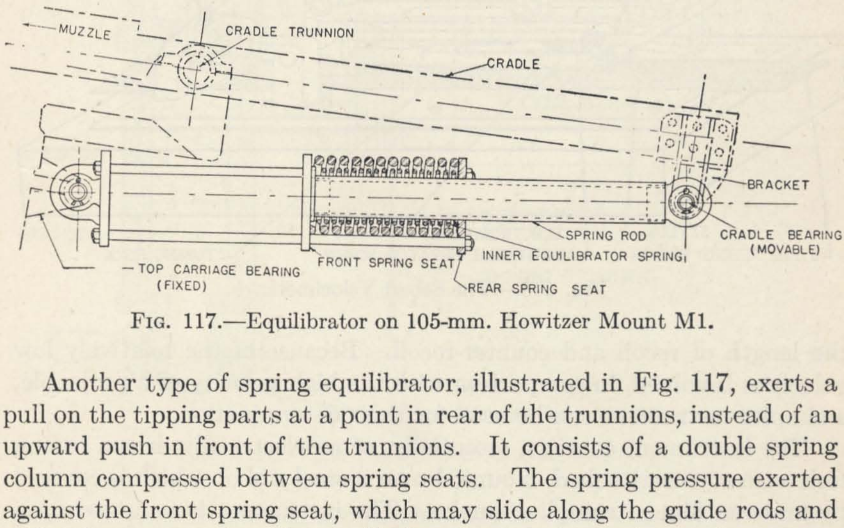


FIG. 117.—Equilibrator on 105-mm. Howitzer Mount M1.

Another type of spring equilibrator, illustrated in Fig. 117, exerts a pull on the tipping parts at a point in rear of the trunnions, instead of an upward push in front of the trunnions. It consists of a double spring column compressed between spring seats. The spring pressure exerted against the front spring seat, which may slide along the guide rods and which is connected to the cradle bracket by the spring rod, tends to pull the rear end of the cradle towards the equilibrator bearing in the top carriage. As the howitzer is elevated, the center of mass of the tipping parts approaches the vertical plane of the trunnions, decreasing the muzzle preponderance. At the same time, the spring rod and front spring seat are moved to the left, permitting the spring column to expand and reducing the balancing force exerted by the springs. This insures low and uniform handwheel effort throughout the range of elevation of the piece.

Pneumatic equilibrators operate similarly. The system usually consists of two gas-filled telescoping cylinders with suitable packing to confine the compressed gas.

The equilibrator is not a part of the recoil system of a gun and, necessarily, the equilibrator bearings must be in non-recoiling parts. The subject is considered at this place in the text, however, rather than in the chapter on artillery, because of its connection with the recoil problem at high firing elevations.

MEASUREMENT OF RECOIL VELOCITY AND PRESSURE

232. The Sebert Velocimeter.—Measurement of the velocities of recoil and counter-recoil is made by use of the Sebert Velocimeter illustrated in Fig. 118. A complete time-travel record is made throughout

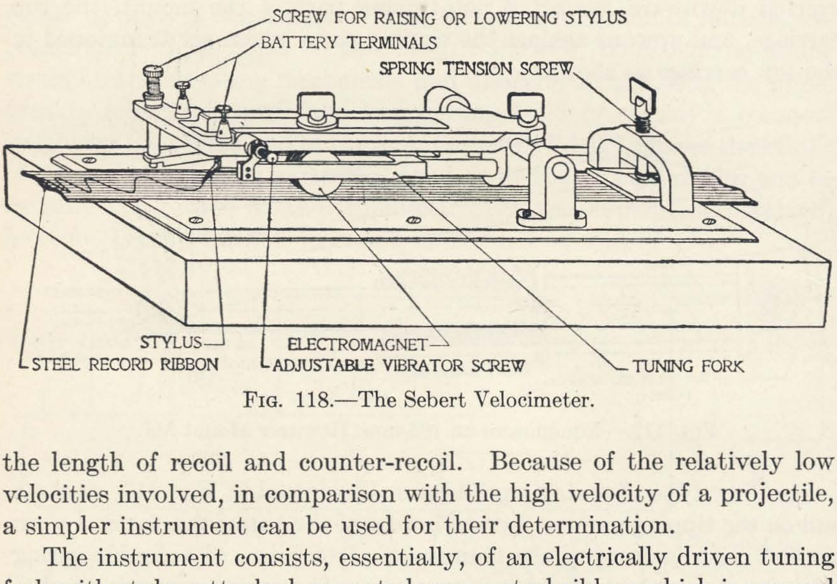


FIG. 118.—The Sebert Velocimeter.

the length of recoil and counter-recoil. Because of the relatively low velocities involved, in comparison with the high velocity of a projectile, a simpler instrument can be used for their determination.

The instrument consists, essentially, of an electrically driven tuning fork with stylus attached, mounted over a steel ribbon which is covered by an even film of camphor smoke. The instrument is mounted on a non-recoiling part of the gun mount and remains in place, but the steel record ribbon is attached to the gun or other recoiling part. The record is taken as the ribbon is pulled along under the vibrating fork and stylus. In the measurement of counter-recoil velocities, the instrument is set up with the stylus end pointing towards the muzzle of the gun; a rod attached to the gun passes through a ratchet device on the front end of the ribbon. During recoil, the rod passes freely through the device and the ribbon remains stationary. In counter-recoil, however, the ratchet engages the rod and the ribbon is drawn forward to make the record.

A tuning fork of 500 frequency is used in recoil measurements, and one of 100 frequency for counter-recoil. When the frequency is known, the record establishes the complete time-distance relation, from which a time-distance curve can be plotted. From this the time-velocity and velocity-distance relations are computed and the curves plotted.

233. The Tabor Indicator.—To obtain a record of the oil pressure in the recoil cylinder, as a function of the travel of the gun in recoil, a com-

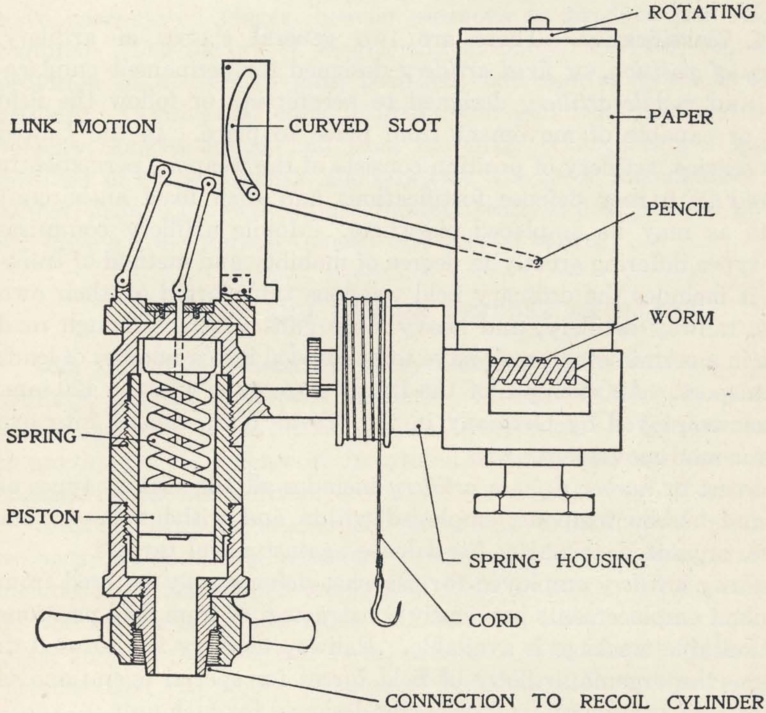


FIG. 119.—The Tabor Steam Engine Indicator.

mercial type of steam engine indicator may be used, as shown in Fig. 119. When the indicator is connected to the recoil cylinder, variations in oil pressure indicated by the movement of the piston against the calibrated spring are recorded on a drum. The drum is rotated by the action of a cord attached to the recoiling gun, the wheel and worm slowing the rotation so that there is slightly less than one revolution during recoil. The indicator being calibrated, the diagram gives the pressure-distance recoiled relation. The area under the curve represents the total work performed by the recoil cylinder.

CHAPTER VIII

ARTILLERY

234. Classification.—There are two general classes of artillery, *artillery of position*, or *fixed artillery* designed for permanent emplacement, and *mobile artillery* designed to accompany or follow the field forces or capable of movement from place to place. In the United States service, artillery of position consists of the weapons permanently mounted in harbor defense fortifications and such fixed antiaircraft mounts as may be emplaced elsewhere. Mobile artillery comprises many types differing greatly in degree of mobility and method of transport; it includes the ordinary field weapons transported on their own wheels, railway artillery, and heavy siege guns which, although road mobile in a certain sense, may have to be divided into a number of loads for transport. An example of the heavy siege guns was the 420-mm. howitzer employed by Germany in the World War, divided into five loads for road movement.

Seacoast or *harbor defense artillery* includes all the various types of fixed and mobile weapons, employed within and without the harbor defense, organized primarily for defense against naval targets.

Railway artillery employed for seacoast defense may be fired from permanent emplacements previously constructed, or from field positions where suitable trackage is available. Railway artillery is also used to reenforce the organic artillery of field forces for special operations as required, and types may be specifically designed for such use.

Antiaircraft artillery includes fixed mounts permanently emplaced and mobile mounts. Its mission is to provide local defense for ground forces, military establishments, and important areas, works, facilities, etc., against enemy aviation.

The weapons used as *field artillery* include light, medium, and heavy types. Their mission is to provide the fire power necessary to assist other ground forces in combat. Certain of these weapons are employed also as mobile seacoast artillery.

The classification of *gun*, *howitzer*, and *mortar* no longer conveys the precise meaning it once did. As formerly defined, a gun was a long, high-velocity weapon fired at elevations not exceeding 20°; a howitzer

of equal caliber was a shorter, lighter weapon, firing at higher elevations than the gun, with less velocity, and at targets that could not be reached by direct fire; the mortar was a still shorter weapon, designed to fire at elevations up to 65° and to give plunging fire on the target. The distinction between gun and howitzer is now less marked. The modern gun carriage permits firings at high elevations. For example, the 16-in. seacoast gun can be fired at elevations up to 65°, and antiaircraft guns up to 85°. On the other hand, the increased ranges demanded of howitzers have necessitated longer, heavier weapons to produce the velocities required. The factors of weight and mobility, however, still justify provision of distinctive gun, howitzer, and mortar types of mobile artillery. Considering equal calibers, the gun will have the highest velocity, longest range, and least mobility. Considering a gun and howitzer of equal mobility, the howitzer will be of considerably larger caliber, firing a projectile approximately twice as heavy as the gun, but will have a lower muzzle velocity and shorter range.

SEACOAST AND HARBOR DEFENSE ARTILLERY

235. General.—Seacoast artillery includes fixed armament, railroad artillery, and motor-drawn artillery. Mobile artillery is employed within and without the harbor defense to reenforce the fixed armament, to provide for the defense of unfortified harbors, and to support troops engaged in seacoast defense.

Seacoast artillery is classified according to caliber of weapon as *primary armament* and *secondary armament.* The primary armament includes fixed and mobile weapons of 12-in. or larger caliber, employed for the attack of capital ships. It includes 12-in., 14-in., and 16-in. guns, 16-in. howitzers, and 12-in. mortars. The secondary armament includes fixed and mobile weapons of less than 12-in. caliber, employed against lightly armored or unarmored vessels, and for the protection of mine fields and submarine nets, and for defense against landings. It includes 3-in., 6-in., 8-in., and 10-in. guns, 8-in. railway guns, and 155-mm. tractor-drawn guns.

Seacoast artillery is characterized by its ability to concentrate great fire power on naval targets, to shift rapidly from one target to another, and by the long range and great power of its weapons, and the strategical mobility of its mobile armament. Its superiority over naval fire power, long contended by artillerymen, was demonstrated during the World War by the unsuccessful naval attacks against the Turkish coast defenses at the Dardanelles and against the German defenses on the Belgian coast. Seacoast artillery has certain defensive limitations, how-

FIXED AND RAILWAY ARTILLERY

Caliber and Type	Cannon: Model	Cannon: Construction	Cannon: Length (Calibers)	Cannon: Weight (Tons)	Carriage: Type	Carriage: Model	Recuperator	Weight of Charge (Lbs.)	Weight of Projectile (Lbs.)	Muzzle Velocity (Ft. per sec.)	Muzzle Energy (Ft.-long tons)	Elevation: Max.	Elevation: Min.	Maximum Chamber Pressure (Lb. per sq. in.)	Maximum Range (Yards)
16-in. Gun	1919 MII MIII	Wire	50	190	Barbette	1919	Pneumatic	832	2340	2700	118,400	65°	−7°	38,000	49,140
16-in. Gun	1919	Wire	50	170	Disappearing	1917	Counterweight	832	2340	2700	118,400	30°	−5°	38,000	41,600
16-in. Howitzer	1920	Built-up	25	98	Barbette	1920	Pneumatic	296	2100	1950	55,400	65°	−7°	38,000	24,500
14-in. Gun	1920 MII	Built-up	50	117	Railway	1920	Pneumatic	460	1560	2650	76,000	50°	−7°	38,000	42,280
14-in. Gun	1910	Wire	40	69	Disappearing	1907MI	Counterweight	435	1660	2350	63,630	20°	−5°	38,000	23,000
14-in. Gun	1909	Wire	40	69	Turret	1909	Spring	435	1660	2350	63,630	15°	−1°	38,000	19,200
12-in. Mortar	1912	Wire	15	17	Mortar	1896MIII	Spring	89	700	1800	15,750	65°	45°	37,000	17,900
12-in. Mortar	1890MI	Built-up	10	15	Railway	1918	Pneumatic	64	700	1500	10,930	65°	20°	37,000	14,650
12-in. Gun	1895MI	Built-up	35	59	Barbette	1917	Spring	270	1070	2250	37,600	35°	0°	38,000	27,600
12-in. Gun	1895	Built-up	35	58	Disappearing	1901	Counterweight	270	1070	2250	37,600	15°	0°	38,000	17,400
12-in. Gun	1895MIAI	Built-up	35	60	Railway	1918	Pneumatic	270	975	2275	35,000	38°	15°	38,000	30,000
8-in. Gun	Mk. VI	Built-up	45	27½	{Railway / Barbette}	{M1 / M1}	Pneumatic	110	260	2750	13,600	45°	0°	38,000	27,550
6-in. Gun	1908	Wire	45	11	Disappearing	1905MII	Counterweight	30.0	108	2600	5,070	15°	−5°	38,000	16,500
105-mm. A. A. Gun	M3	Monotube	60	3¼	Barbette	MI	Spring	10.75	33	2800	1,800	80°	—5°	38,000	{14,000 V. / 20,000 H.}
3-in. A. A. Gun	M4	Cold-worked, loose liner	55	1½	Barbette	M3A1	Spring	5.0	12.7	2800	690	85°	−5°	41,000	{9,700 V. / 14,200 H.}

ever, its fixed armament being immobile, its mobile armament having little tactical mobility, and, when not properly supported, the defensive organization being vulnerable to air attack, to attack by landing parties, and to land attack.

The harbor defenses of the United States and its possessions include guns and carriages of many types, some of which are obsolescent. The accompanying table illustrates the diversity of types; however, regardless of age or model, all have value and power and, until replaced by new or more appropriate weapons, have definite defensive missions to perform. The present policy is to provide fixed 16-in. guns and 14-in. railway guns as primary armament, and fixed 8-in. guns, 8-in. railway guns, and 155-mm. tractor-drawn guns as secondary armament. The available 14-in. fixed guns, and the 12-in. guns and mortars, fixed and railway, reenforce the standard weapons and may be used as primary armament for the defense of harbors and coastal areas of less strategic importance. Similarly, installed 6-in. and 10-in. fixed guns form part of the secondary armament.

FIXED HARBOR DEFENSE ARMAMENT

236. Types of Mounts.—Fixed armament has the advantage of being located where needed, based upon tactical and strategic considerations, and is ready for use when needed. It can be afforded effective concrete and earth protection if desired, the use of permanently installed communications, stations, and fire-control equipment is practicable, and electric power is available. The construction can be such as to insure maximum stability in the mount. These advantages increase the accuracy and rate of fire. However, fixed armament is immobile and cannot be transported elsewhere for use, its location may be known to the enemy, and it may lack concealment. Attainment of effective fire is the primary consideration in determining location, but the field of fire may be restricted by the type of carriage or emplacement, and the range limited by the carriage, as in the disappearing guns. Modern emplacements and carriages generally are designed for all-around fire, and the carriages are designed to permit firings at high elevations.

There are two principal types of carriages, the *disappearing* carriage and the *barbette* carriage. The recoil of the gun mounted on the disappearing carriage withdraws the gun to its loading position behind the parapet and below its crest. When loaded, the gun is raised to its firing position. This type of mounting gave satisfactory protection to matériel and personnel at the time when naval weapons were limited to relatively short ranges and firing elevations of approximately 15°. However, the carriages were complicated, the field of fire limited, and

elevations above approximately 30° impracticable of attainment. These limitations of the disappearing carriage, together with the increased ranges and elevations of naval guns and increased angles of fall, which minimized the protection previously afforded by the concrete and earth, have resulted in the abandonment of this type of mount for future construction. Although the barbette mount has been used for all fixed artillery designed since the World War, many disappearing carriages are still emplaced in our fortifications, mounting modern and efficient guns, and constituting valuable fixed defensive armament. In the barbette carriage no mechanism is provided for the withdrawal of the gun from its firing position. Although it may be afforded partial protection by a parapet, the modern practice is to design the mount as simple and inconspicuous as possible, and to locate it in the open without protection.

General Characteristics of Mounts.—In general, the mount consists of a heavy base or *base ring* bolted rigidly to the concrete emplacement and of a gun-supporting superstructure resting on the base and capable of moving in azimuth upon it. In the larger mounts the base ring may be made in several sections, which are bolted together for assembly. The construction and method of emplacement will be apparent from the illustrations of carriages to be discussed later. The top of the base ring forms a path upon which are mounted conical *rollers* which support the superstructure and all *traversing parts* of the carriage. Resting on these rollers and revolving thereon is the *racer*, to which is bolted the *top carriage*, or equivalent member termed pivot yoke, side frames, etc., in various designs. The top carriage supports the *tipping parts*. In all modern designs, the gun is supported in a cradle, through which it slides in recoil. The cradle forms the housing for the recoil and recuperator mechanisms. The trunnions of the cradle rest in trunnion bearings in the top carriage, or equivalent member, which permits movement of the gun and cradle in elevation.

The mount is traversed and the gun is elevated by means of traversing and elevating mechanisms mounted on the top carriage or other traversing part, which include suitable gear trains meshed, respectively, with a traversing rack on the base ring and an elevating rack on the cradle.

Electric power may be utilized to elevate, traverse, and load the gun, and compressed air to actuate the breech mechanism.

The mounts to be described incorporate the above general features although the design details vary considerably. A description of representative types follows.

237. Seacoast Mortars.—Modern capital ships have heavy side armor which can withstand a considerable amount of fire; their rela-

tively thin deck armor offers an attractive target to artillery. The weapons best adapted for this deck armor attack are the seacoast howitzers and mortars, comparatively short weapons which are able to fire at high angles of elevation, and with less velocity than guns of equal caliber. The fairly thin-walled projectiles descending almost vertically on the armored deck penetrate readily, and, equipped with delay-action fuzes and carrying large high explosive bursting charges, can produce enormous destructive effects within the interior of the ship.

A considerable number of 12-in. mortars are installed within the harbor defenses. They can be afforded excellent concealment and protection against gun fire; they have all-around fire, are less expensive, have longer accuracy life than guns, the carriages are simple, and they are well-suited for the attack of the most vulnerable part of the ship. On the other hand the maximum range is short, only indirect fire is possible, certain difficulties of fire adjustment are encountered, and zone fire is necessary. Firing only at elevations between 45° and 65°, a limited range only could be covered by a fixed charge of powder and fixed weight of projectile. Accordingly, several different weights of charge and two weights of projectile are employed, and the field of fire is divided up into a number of overlapping range zones, the limits of each zone being reached with a given charge and projectile by mortar elevations varying from 45° to 65°. The difficulties involved in directing fire on fast-moving targets passing rapidly from one zone to another limit the value of the mortar. None have been built within recent years.

238. The 12-in. Mortar Carriage, Model 1896.—This carriage, illustrated in Fig. 120, has been used to mount the 12-in. Mortars, Models 1890 and 1912. The former is of built-up design, 10 calibers in length; the latter is a wire-wound type, 15 calibers in length, with greater muzzle velocity and longer range.

The mortar is supported by its trunnions in the upper ends of the two arms of the yoke *d*, which is hinged between two brackets on the front part of the racer. The racer rests on live rollers on the base ring. Five sets of coiled springs, bearing at their bottom ends against an oscillating spring support trunnioned in brackets bolted to the bottom of the racer, act at their top against a rocking cap piece *c* in the yoke. These springs support the mortar in its firing position and return it to battery after recoil.

Two recoil cylinders *h* are trunnioned in bearings extending up from the top of the racer. A frame *f* bolted to each cylinder guides the cross-head *o* which connects the upper end of the piston rod and the pin *r* extending outward from the mortar trunnion. The five spring columns constitute the recuperator mechanism.

The carriage is traversed on the conical rollers by a handwheel, which actuates a vertical shaft having a pinion p at its lower end, engaged in a circular rack attached to the base ring. The elevating mechanism comprises two handwheels mounted on a single shaft, connected by suitable gearing to a pinion meshed with the elevating rack segment attached to the bottom of the mortar.

Other Mortars.—The 12-in. Mortar Carriage, Model of 1908, was designed to permit firings at all elevations from 0° to 65°, to permit the mortar to be brought to 0° elevation for loading without interfering with continuous laying in elevation, thus increasing the rate of fire, and to

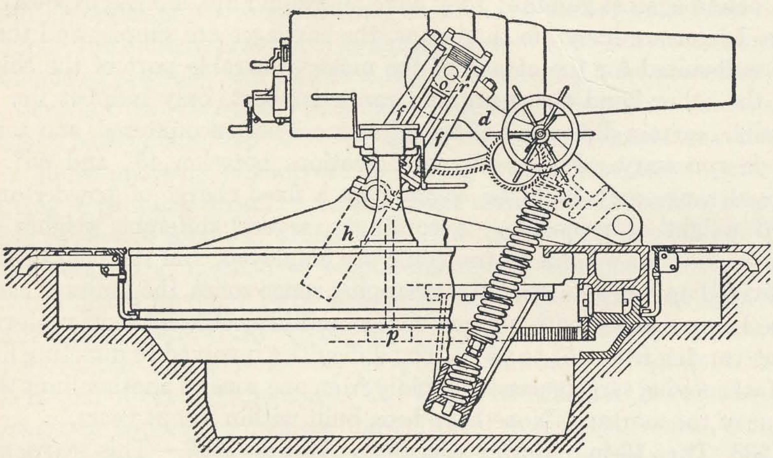


FIG. 120.—12-in. Mortar on 12-in. Mortar Carriage, Model of 1896.

provide a modern system of cradle recoil. Few of these carriages were constructed.

239. 16-in. Disappearing Carriage, Model of 1917.—There are several different models of disappearing carriages in the harbor defenses, mounting a considerable number of 6-in., 12-in., 14-in., and 16-in. guns and obsolescent 8-in. and 10-in. guns. The advantages and disadvantages of this type of mount, and the consideration which led to its abandonment in favor of the barbette carriage, so far as post-war construction was concerned, have already been discussed briefly. The general features of design and operation are similar in the various disappearing carriages, and are well illustrated in the 16-in. Disappearing Carriage, Model of 1917, shown in Fig. 121, the latest built.

The annular base ring, which surrounds the well left in the concrete emplacement, is 24 ft. in diameter and forms the circular pathway upon which the 30 traversing rollers move. These rollers, which are called

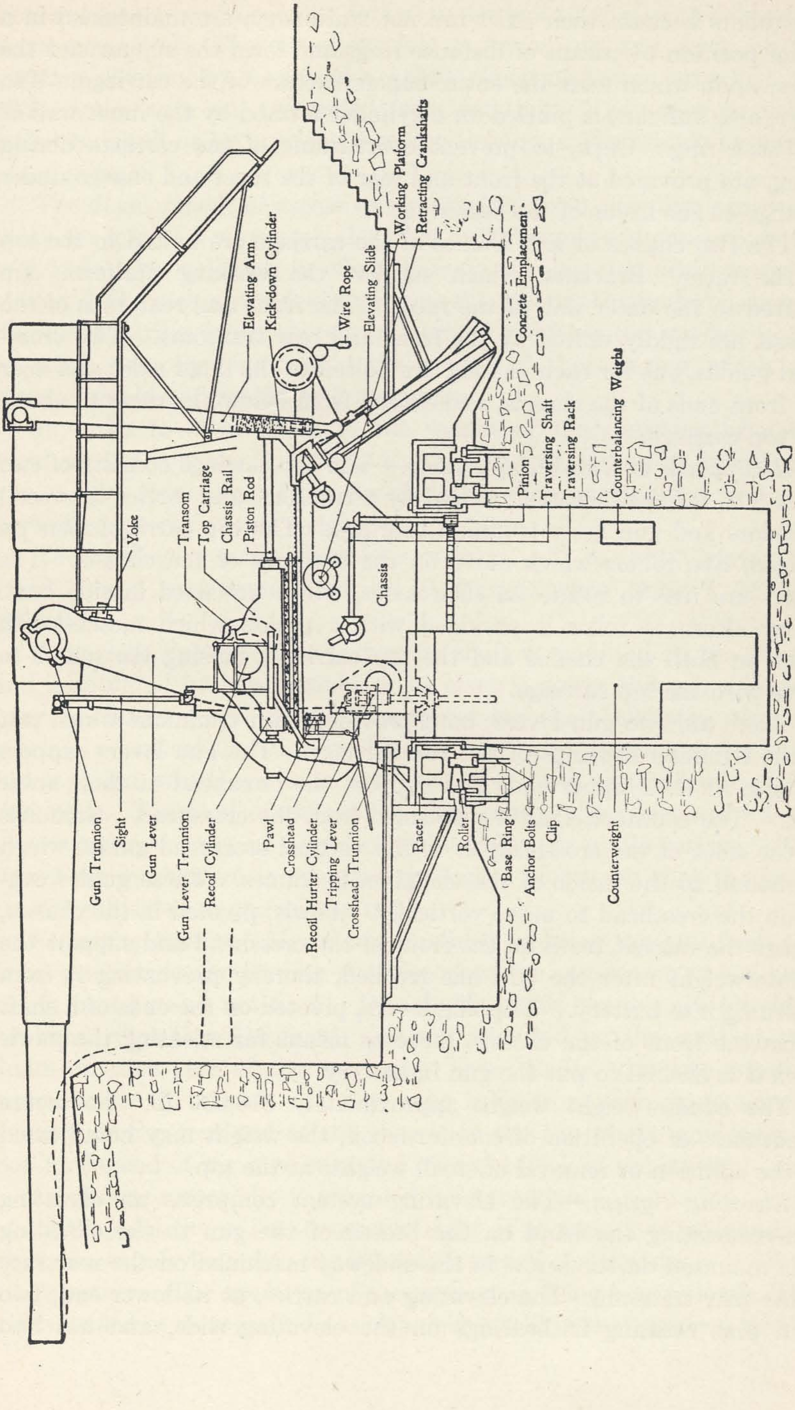


FIG. 121.—16-in. Gun on 16-in. Disappearing Carriage, Model of 1917.

live rollers because their axles are not stationary, are maintained in a radial position by means of distance rings and form the support for the racer, upon which rests the entire superstructure of the carriage. The racer, also annular, is pintled on a cylinder formed by the inner wall of the base ring. Clips, to prevent overturning of the carriage during firing, are provided at the front and rear of the racer and engage under a flange on the inside of the base ring.

The two chassis or side frames of the carriage are bolted to the top of the racer. Brackets, which support the working platform, are secured to the outer wall of the racer. The front and rear ends of the chassis are rigidly united by the front and rear transoms. Two crosshead guides, one for each chassis, are bolted to the inner sides and near the front ends of the chassis, and extend from below the racer to above the top carriage.

Recuperator or Gun-lifting System.—The top carriage consists of two sides (one for each chassis), united by a transom, and carries the recoil cylinders and gun lever trunnion bearings. The top carriage rests on flanged, live rollers which move on the top rails of the chassis. The rollers are free to rotate on their axles, which are fixed in side bars. Every alternate roller is provided with a pinion which meshes with racks on both the chassis and the top carriage, causing the rollers to move with the top carriage.

There are two gun levers, both provided with trunnions which rest in the trunnion bearings of the top carriage. The gun levers support the gun at their upper ends and support the crosshead at their lower ends. The counterweight is suspended from the crosshead. Channels on the sides of the crosshead fit in the vertical crosshead guides which are bolted to the inside of the chassis side frames. These guides constrain the crosshead to move vertically. Pawls, pivoted in the chassis, engage the ratchet teeth on the front of the crosshead and support the counterweight after the gun has recoiled, thereby preventing it from returning into battery. Tripping levers, pivoted on the ends of a shaft across the front of the chassis, serve as means for releasing the pawls when it is desired to put the gun in battery.

The counterweight weighs approximately 610,000 lb. To secure smoothness of operation of counter-recoil, the weight may be adjusted by the addition or removal of small weights at the top.

Elevating System.—The elevating system comprises an elevating arm connecting the band on the breech of the gun to the elevating slide mounted on the screw in the slideway machined on the rear face of the rear transom. The elevating arm carries, at its lower end, two fixed pins rotating in bearings on the elevating slide, and has two

bronze-bushed bearings at its forked upper end to engage the elevating band trunnions. The elevating slide is moved up and down on the circular slideway by means of a heavy elevating screw, on which the slide moves as a nut prevented from rotating. The screw is driven either by hand or by an electric motor through a Waterbury hydraulic speed gear.

The development of excessive stresses in a fixed elevating arm when firing the gun at a maximum elevation of 30° requires the incorporation of a kick-down cylinder, in effect making the elevating arm somewhat elastic. The kick-down device permits the rear of the gun to be slightly depressed during firing, thereby materially reducing the stresses in the elevating arm by lengthening the period of time during which the stresses would be brought to a maximum.

In order to counterbalance the weight of the elevating arm and band, and to equalize the efforts required to elevate and to depress the gun, a wire rope passes from the elevating slide over pulleys and supports a counterbalancing weight.

The carriage permits elevations of from $-5°$ to $+30°$, giving the 16-in. gun a maximum range of 40,000 yd. when firing a 2400-lb. projectile.

Traversing System.—The traversing shaft is mounted on the chassis and is actuated by hand cranks or by electric power through a Waterbury hydraulic speed gear. The traversing shaft operates, through gearing, a vertical shaft fastened to the racer and carrying at its lower end a pinion, which works in a circular rack fixed to the inside of the base ring. Rotation of the pinion thus causes the racer and all the superstructure of the carriage to revolve about its pintle surface. The traversing mechanism is operated through a clutch, so that the gears are not subjected to excessive strains.

Retracting System.—Means are provided to bring the gun from the firing position to the loading position when for any reason it has been put in battery and not fired. Detachable crank handles are provided for hand retraction (16 men), and are mounted on the ends of two shafts on each side of the carriage. These shafts turn two winding drums inside the chassis. A wire rope leads from each drum around a pulley at the rear end of the chassis to the top of the gun lever, a loop in the end of the rope engaging over the hook of the lever.

An electric motor also is provided for retraction.

Sighting System.—The telescopic sight is mounted on a standard which is securely bolted to the left side frame of the chassis.

Operation.—The operation of the carriage in firing is as follows: The gun is loaded in its retracted position, being held in that position by the

pawls engaged in the notches on the crosshead. After the gun is loaded, the tripping levers are raised, withdrawing the pawls and releasing the counterweight. The counterweight falls and the top carriage, carrying the gun lever trunnions, moves forward on its rollers, the last part of its motion being so controlled by the counter-recoil buffers in the rear cylinder heads that the top carriage comes to rest without shock. The movement of the gun levers is such that the gun is lifted to the in-battery position above the parapet.

After the piece is fired, the movements are reversed in direction. The recoil forces the gun to the rear, the top carriage rolls back on the chassis rails, and the counterweight rises vertically until the gun resumes the loading position, when the pawls engage the ratchet teeth on the crosshead.

In the movement either way, the upper ends of the gun levers describe the arc of an ellipse. The path of the muzzle of the gun, indicated in Fig. 121, is effected by the constraint of the elevating arm. The ellipse is the most favorable path to follow in the movement of a gun on a disappearing carriage. From the firing position, the movement at first is almost horizontally backward, the movement downward occurring principally in the latter part of recoil. Therefore, the carriage that moves the gun in an elliptical or similar path can be brought nearer to the parapet and thus receive the maximum protection.

The energy of recoil is absorbed partly by raising the counterweight and moving the gun, gun levers, and top carriage, but principally by the resistance provided by the hydraulic recoil cylinders. Near the end of recoil, when the movement of the gun is almost vertically downward, the effect of the horizontal cylinders is not great and at this time two hydraulic hurter cylinders come into action to control the final stop. The hurter cylinders are arranged on the outside of each chassis, opposite the guides, so as to be driven upward over fixed pistons, thus arresting the last 6.4 in. of movement of the counterweight and preventing undue shock at the end of recoil.

The rate of fire of the 16-in. gun mounted on this carriage is one shot per minute. The total maximum force of the powder gases is 8,700,000 lb. and the total constant piston-rod pull is 615,000 lb.

240. Barbette Carriages.—There are many models of barbette carriages emplaced in the harbor defenses, mounting 3-in., 6-in., 12-in., 14-in., and 16-in. guns, and the 16-in. howitzer. For new harbor defense installations, the 16-in. and 8-in. guns on barbette carriages are the standard primary and secondary weapons.

Pedestal mounts.—The 3-in. and 6-in. guns are mounted on simple carriages, the general construction features of which are shown in Fig.

122. The gun is supported in a cradle *c*, through which it slides in recoil. The cradle, which carries the recoil and recuperator cylinders, is mounted by its trunnions in bearings in the two arms of the pivot yoke *y*. The pivot yoke is supported and revolves on roller bearings or a ball-thrust bearing at the bottom of the pedestal, *r*, Fig. 122. The pedestal of cast or forged steel performs the same functions as the base ring in other carriages, and is bolted rigidly to the concrete platform. The traversing rack *t*, in the form of a circular worm wheel, is held to the top of the pedestal by an adjustable friction band; similarly, the worm wheel in the elevating gear is held between adjustable friction disks. Such friction devices permit slipping in case of undue strain on the worm wheel teeth, preventing damage.

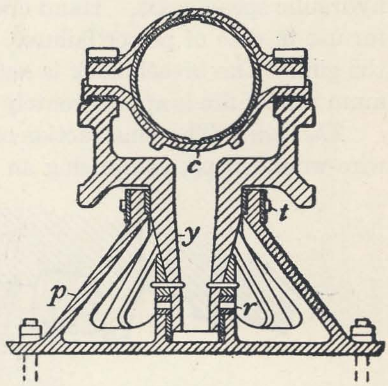


FIG. 122.

Turret Mounts.—For certain harbor or seacoast defense sites, turret mountings have been used. A number of such mounts were installed by Germany along the coast of Belgium during the World War. This type, mounting two 14-in. guns, has been used to a very small extent in the United States service.

The turrets do not differ in general design from naval turrets of the corresponding period except that for land use there is no restriction on size and weight and the mounts can be made larger and heavier if desired. The magazines, handling rooms, and electrical compartments are placed the necessary distance underground for protection, and the ammunition is raised to the gun on hoists by methods similar to those used on naval vessels.

The barbette of the turret is protected by an encircling band of armor anchored in the concrete fortification, and heavy armor plates are attached to the front, sides, back, and top of the turret structure and rotate with it. The entire turret structure rotates 360° in azimuth on a heavy base ring. The all-around protection afforded by the concrete and armor against gun fire and aircraft bombing is an important advantage of this type of installation. The cost of mounts and fortifications is, however, very great compared to that of simple barbette carriages of modern design, and this factor is largely responsible for the limited use of turrets in our service.

241. The 16-in. Gun, Model 1919, MII or MIII, on Barbette Carriage, Model 1919.—This is the standard weapon, primary armament,

for new harbor defense installation. The carriage permits all-around fire, at elevations from $-7°$ to $+65°$. The gun fires a 2340-lb. armor piercing projectile at a muzzle velocity of 2700 f.s.; the powder charge of 832 lb. of pyro powder produces a maximum chamber pressure of 38,000 lb. per sq. in. The maximum range of approximately 50,000 yd. (28 miles) is attained at a gun elevation of 53°. Electric power is used for elevating, traversing, and loading, the drive being through Waterbury hydraulic speed gears. Hand cranks for manual operation are provided for use in case of power failure. A mechanical rammer is used to load the gun. The breechblock is actuated by compressed air. The maximum rate of fire is approximately one shot every 50 seconds.

The Gun.—The construction of the gun was shown by Fig. 56. It is a wire-wound type, comprising an A-tube, a B-tube, a short jacket over

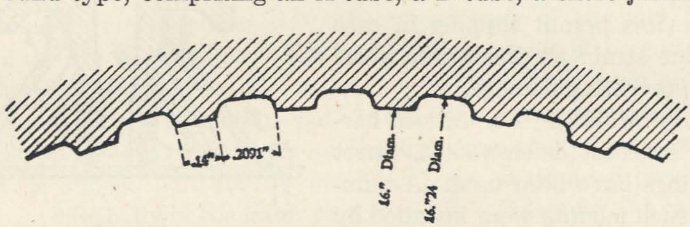


FIG. 123.—Lands and Grooves of 16-in. Gun.

the rear end of the B-tube, a wire envelope from breech to muzzle, and various hoops and locking rings. The powder chamber has a capacity of 40,900 cu. in. The interior of the jacket at the rear end is step-threaded to receive a Welin type of breechblock. The bore is rifled with 144 grooves, uniform twist of one turn in 30 calibers, producing a projectile rotation of 4050 r.p.m. at the muzzle. The rifling grooves have a width of 0.2091 in. and a depth of 0.12 in.; the lands have a width of 0.14 in. The form is indicated in Fig. 123. A heavy lead-filled recoil band or counterweight is attached to the breech end of the gun to permit mounting well forward in the cradle, with the breech close to the cradle trunnions. The total weight of the gun is 340,600 lb. without the recoil band; its total length is 826.8 in., and the approximate droop at the muzzle, with the gun supported in the cradle at 0° elevation, is 0.6 in.

Breech Mechanism.—The breech mechanism of the Welin stepped-thread type, and the Firing Lock, Mk. I, have been described in Chapter VI.

Base Ring—Racer—Side Frames.—The general construction is shown in Figs. 124 and 125. The base ring is composed of four sections, rigidly bolted together and anchored to a concrete foundation. The upper surface forms a suitable bearing for the 44 conical rollers which support

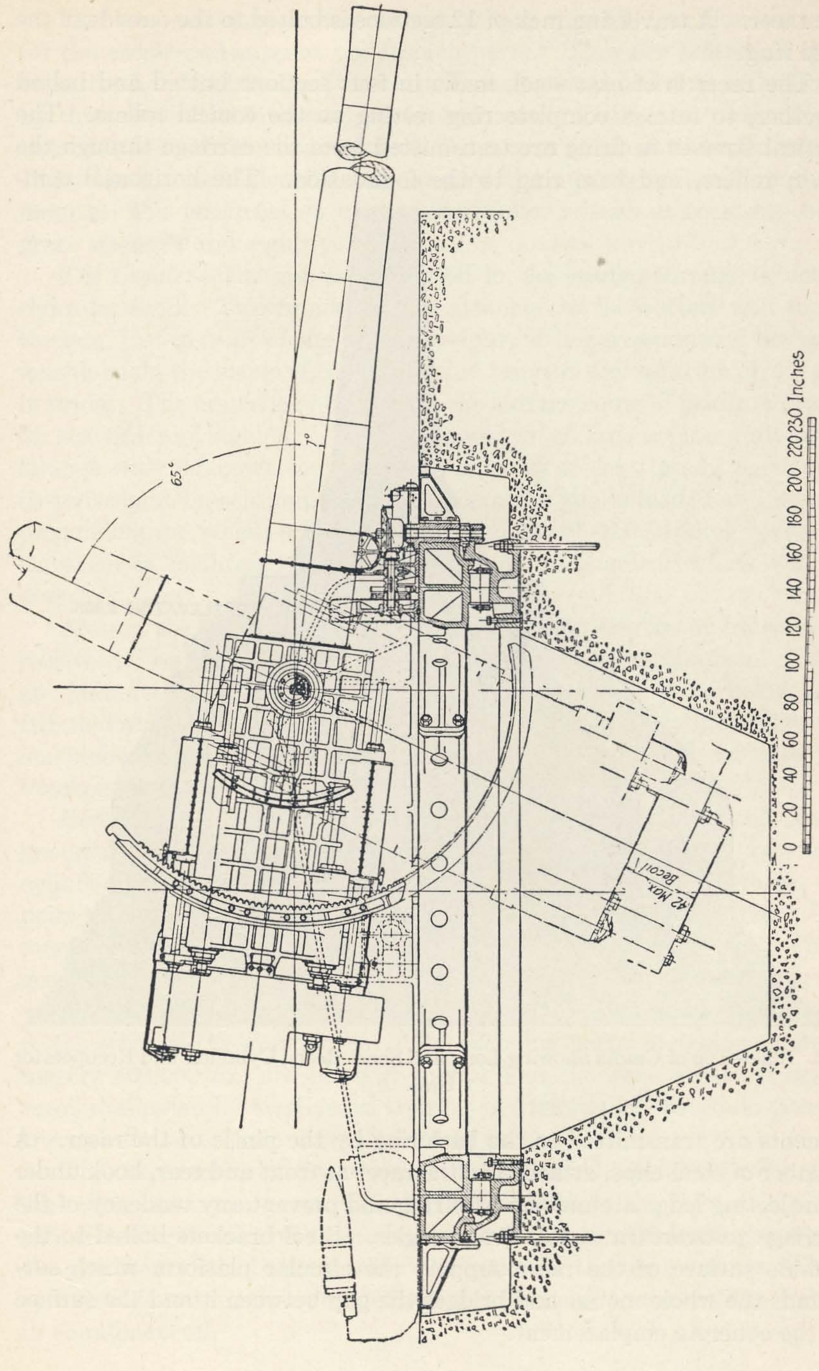


FIG. 124.—16-in. Barbette Carriage, Model of 1919.

the racer. A traversing rack of 12 sections is bolted to the outside of the base ring.

The racer is of cast steel, made in four sections butted and bolted together, to form a complete ring resting on the conical rollers. The vertical stresses in firing are transmitted from the carriage through the racer, rollers, and base ring to the foundation. The horizontal com-

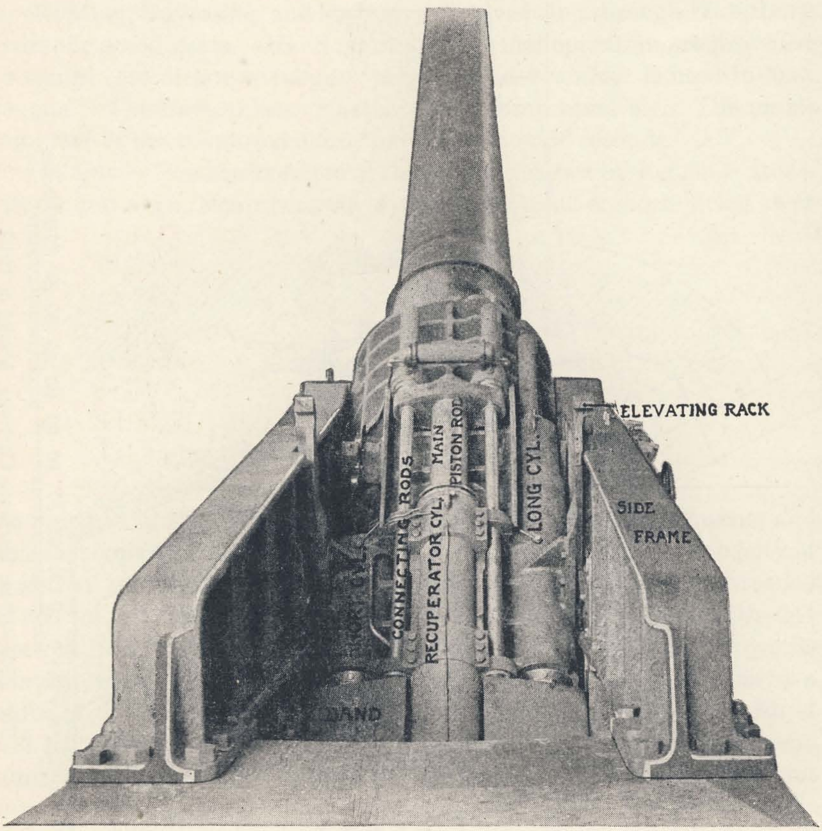


FIG. 125.—Top of Cradle Showing Long and Short Recoil Cylinders and Recuperator Unit.

ponents are transmitted to the base ring by the pintle of the racer. A number of steel clips, attached to the racer at front and rear, hook under a projecting ledge around the base ring and prevent any tendency of the carriage to overturn at low firing angles. Steel brackets bolted to the outside surface of the racer support the circular platform which surrounds the whole mount and bridges the gap between it and the surface of the concrete emplacement.

The two cast-steel girders or *side frames* provide trunnion bearings for the cradle and support the tipping parts. They are bolted, at their ends, to the annular racer, and are also supported and braced laterally by three steel floor beams which extend outward from the under side of each side frame to the inner surface of the racer to which they are bolted. These beams also stiffen the racer and are the support for the floor of the mount. The construction of the side frames is such as to insure both great strength and rigidity.

The Cradle.—The gun is supported in the cradle, through which it slides in recoil. Two bronze splines attached to the bottom and top of the gun, just in front of the counterweight, fit in corresponding keyways machined on the inside of the cradle and prevent any rotation of the gun in firing. The cradle is of cast steel, the surface being of gridiron design for strength and rigidity. The trunnions, which are cast integral, are so located with reference to the center of mass of the tipping parts that there is slight breech preponderance when the gun is loaded and muzzle preponderance when unloaded. Movement of the tipping parts in elevation is facilitated by the antifriction mechanism which will be described later.

Around the outside of the cradle are cast six sleeves or brackets to receive the six cylinders of the recoil and recuperator mechanism. They are placed three above the center of the cradle and three below, distributed and arranged to balance each other. The six cylinders are not machined in the cradle casting, but are of forged steel set into the brackets or sleeves.

Recoil Mechanism.—The mechanism is of the hydraulic recoil brake, pneumatic recuperator type. The recoil brake consists of two long cylinders and two short cylinders, set into brackets in the cradle, the pairs being arranged diagonally opposite as illustrated in Fig. 125. The rear ends of the pistons are attached to the gun counterweight. Three grooves are machined on the inside of each cylinder, of uniform width but varying depth, through which the oil passes from one side of the piston to the other as the gun recoils. The recoiling parts, weighing approximately 400,000 lb., are brought to rest and the very great energy of recoil dissipated by mechanical friction and friction of the liquid passing through the orifices, in a distance of 42 in.

The construction of the two short cylinders is illustrated in Fig. 126. The oil moves under great pressure from the left to the right side of the piston during recoil, and passes back slowly through the same grooves as the gun moves into battery under the action of the recuperators. These cylinders do not incorporate any buffer mechanism to control the motion in counter-recoil.

The construction of the two long recoil cylinders is illustrated in Fig. 127. A piston rod with two pistons operates in each cylinder. The left or rear half of each cylinder and the left piston are practically identical with the two short cylinders just described, and perform the same function, that of a recoil brake. The portion of each long cylinder to the right of the center performs a different function.

The gun has an elevation range from $-7°$ to $+65°$. The recuperating effort to return the recoiling parts to battery varies with the elevation and is greatest at 65°. Although the conventional dashpot type of buffer would be able to retard the last forward motion of the gun satisfactorily at the high elevations, it could not control the excess

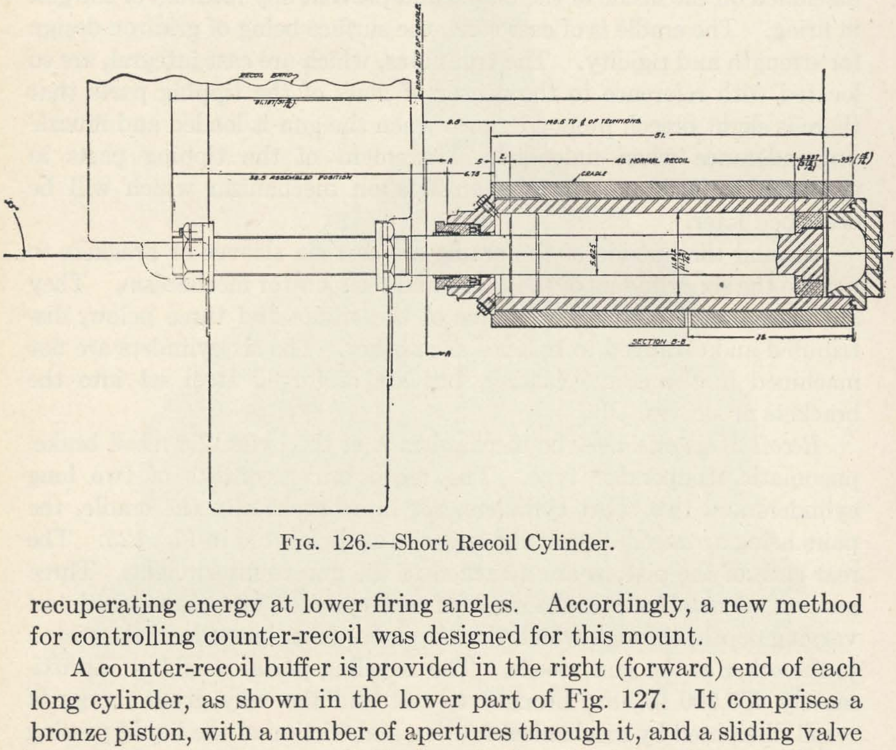


FIG. 126.—Short Recoil Cylinder.

recuperating energy at lower firing angles. Accordingly, a new method for controlling counter-recoil was designed for this mount.

A counter-recoil buffer is provided in the right (forward) end of each long cylinder, as shown in the lower part of Fig. 127. It comprises a bronze piston, with a number of apertures through it, and a sliding valve to close these apertures. During recoil, the oil between the two pistons passes readily through the apertures in the buffer piston and through throttling grooves in the walls of the cylinder. During counter-recoil, however, the sliding valve closes the apertures, and the oil must pass through the restricted orifices afforded by the throttling grooves in the cylinder walls. This buffer mechanism operates satisfactorily at all elevations.

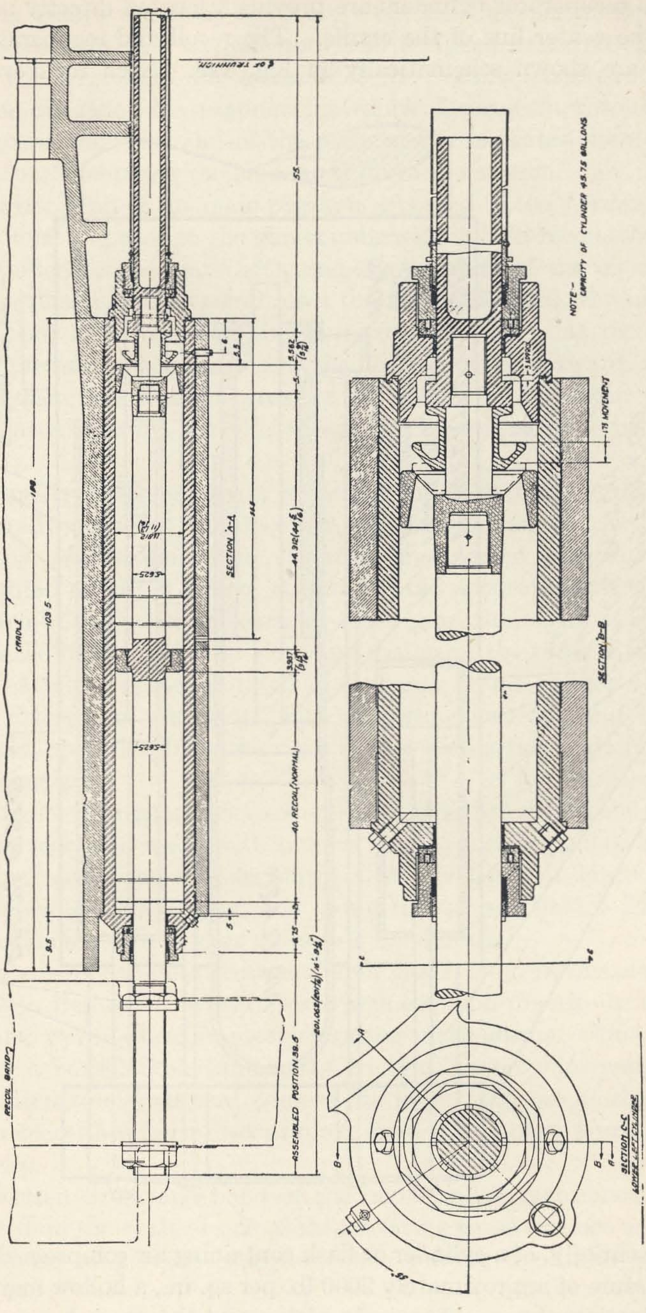


FIG. 127.—Long Recoil Cylinder.

Two recuperator cylinders are provided, located directly above and below the center line of the cradle. The recoil and recuperator mechanisms are shown schematically in Fig. 128. Each recuperator con-

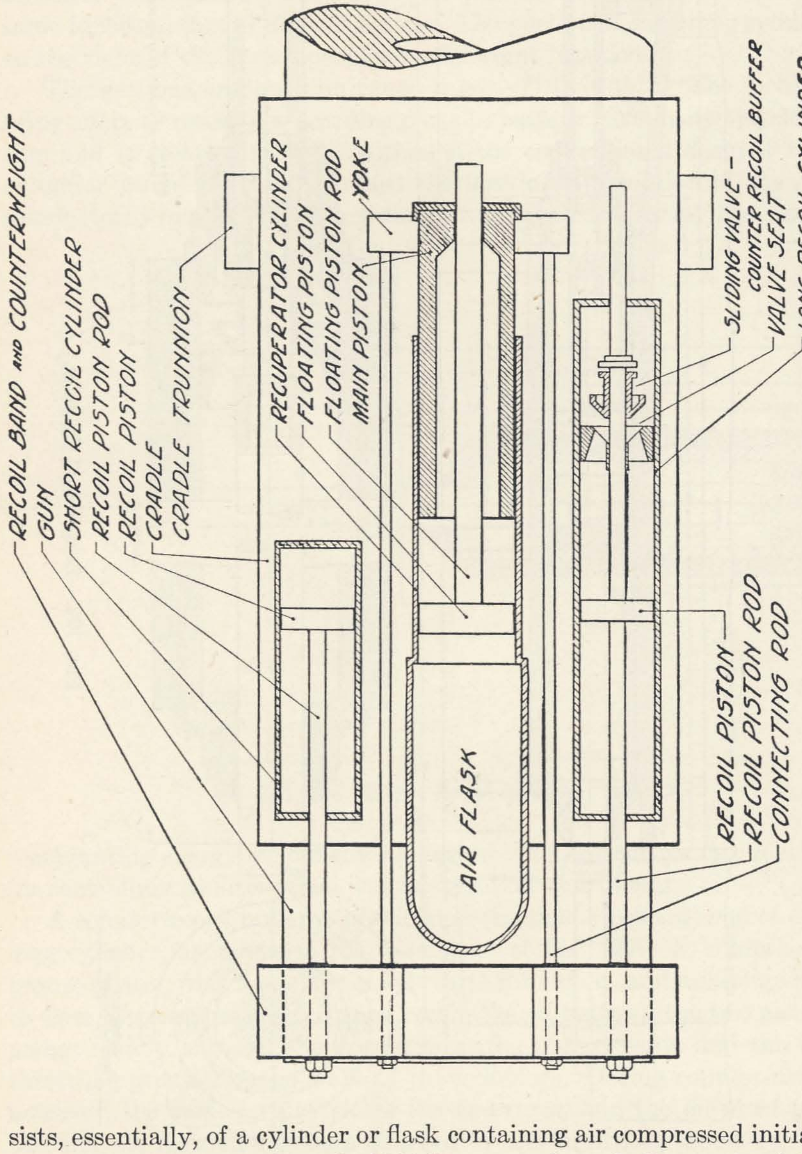


FIG. 128.—16-in. Barbette Carriage Recoil System (Schematic).

sists, essentially, of a cylinder or flask containing air compressed initially to a pressure of approximately 2000 lb. per sq. in., a hollow main piston, and a floating piston. The main piston and the space between it and

the floating piston are filled with oil. The floating piston separates the compressed air from the oil, and is so designed as to prevent the escape of the air. The only purpose of the floating piston rod is to provide an oil gage; the amount by which it projects through the stuffing box at the front end of the main piston indicates the position of the floating piston and the amount of oil in the system.

The forward end of the main piston is attached to the yoke, and the yoke by connecting rods to the gun counterweight. In recoil, the main piston is pulled to the rear (left), and the pressure of the oil against the floating piston further compresses the air in the flask, the pressure rising to about 3140 lb. per sq. in. at maximum recoil. At the end of recoil, the pressure of the air pushes the floating piston forward, and its motion, transmitted through pressure on the oil to the main piston, forces the latter forward, carrying the gun and recoiling parts back into battery.

This same type of recuperator is used on the 16-in. howitzer carriage, the 14-in. railway mount, and in other modern mounts.

Elevating Mechanism.—The elevating mechanism comprises two racks mounted on either side of the cradle, the antifriction mechanism incorporated in the trunnion bearings, speed gear, shafts, trains of gears leading to the handwheel, and elevating motor on the right side of the carriage. A buffer is incorporated in each side frame to stop the gun at either extreme of elevation, without serious jarring; and friction hand brakes, operating from the right side of the carriage, are included in the mechanism.

The circular spur-gear racks are attached to either side of the cradle, toward the rear, and mesh with pinions which, on the right side, lead through spur gears and various clutches to a fast-motion crank, slow-motion handwheel, speed gear, and power motor; and on the left side, through a similar train of spur gears to a hand crank.

It is interesting to note the use of spur gears, only, in this elevating mechanism. Before the World War it was common practice to include a worm and worm wheel in most elevating mechanisms. This device introduced a considerable amount of friction, thereby increasing the effort required to elevate and depress the gun. The use of the worm and worm wheel has been discontinued since it has been found not at all necessary.

The friction drum and band of the hand brakes mentioned above are included on the shaft of one of the elevating gears and act as a slip-friction device to prevent excessive loads coming upon the gears in firing.

Normally, the gun will not be elevated or depressed by hand but by

electric motor through the Waterbury speed gear. By the use of this gear, it is possible to elevate or depress the gun in approximately 10 seconds. It is possible also to reduce the rate of elevation through this gear to such an extent as to obtain the final laying of the gun on the target.

Antifriction Mechanism.—The elevating antifriction mechanism (Fig. 129) consists essentially of a bearing pin, fitted into the main trunnion of the cradle; a nest of rollers (having an inner and an outer sleeve) surrounding the bearing pin; and a trunnion support or crutch, which is stationary. The trunnion support or crutch passes through a vertical slot in the trunnion bearing of the side frame and is supported on the beam, the lower front end of which rests on and may rotate about a steel pin on the side frame and the rear end of which is supported through a steel rod on three pairs of Belleville springs. When the gun is assembled in the carriage, the main trunnions, of course, bear upon the main trunnion bearings, and the friction is very great. If no provision were made for reducing this friction, it would be impossible to elevate the gun except at an exceedingly slow rate through a very great reduction in the gearing. After the gun and antifriction mechanism have been assembled, the rear end of the beam is drawn up by means of the adjusting nuts until a 0.02-in. feeler gage can be inserted between the main trunnion and the main trunnion bearing. The gun is then being supported entirely on the rollers, and the main trunnion is practically floating with reference to its bearing. The coefficient of friction when the bearing is properly adjusted is 0.006 and relatively little effort is required on the elevating handwheel to raise or depress the gun.

When the gun is fired, the Belleville springs are compressed just enough to permit the trunnions to come in contact with the main bearings, and the force of recoil is transmitted to the heavy side frames through the main trunnion bearings.

In designing this elevating mechanism, it was found that the gun could be so balanced as to give a positive muzzle preponderance when empty and a positive breech preponderance when loaded. Thus, after the gun has been fired and the brake band released by pulling up the brake lever, a spin given to the handwheel will cause the gun to drop smoothly to its loading position in approximately 10 seconds. As soon as the gun is loaded, after the brake band is released and the handwheel given a spin, the gun will rise easily to any elevation. It is probable that nothing is gained by this means of elevating and depressing over operation by means of the motor; but, in the event of difficulties with the motor or its possible failure, the gun can be operated, so far as elevating and depressing are concerned, almost as rapidly by hand as by power.

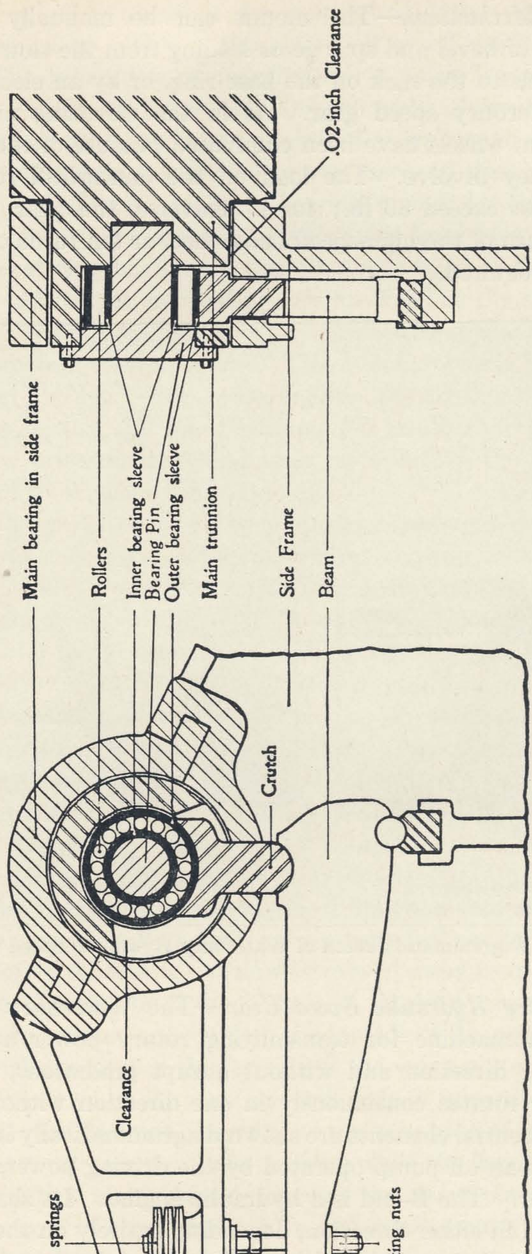


FIG. 129.—Device for Reducing Friction between Cradle Trunnions and Side Frames.

Traversing Mechanism.—The mount can be manually traversed through a train of bevel and spur gears leading from the slow and high-speed handwheels to the rack on the base ring, or by an electric motor through a Waterbury speed gear. As in the elevating mechanism, worms and worm wheels have been eliminated because of the excessive friction that they involve. The load on the handwheel required to traverse does not exceed 30 lb.; for 1° traverse, the gear ratios are such that one turn of the high-speed handwheel or ten turns of the slow handwheel are required.

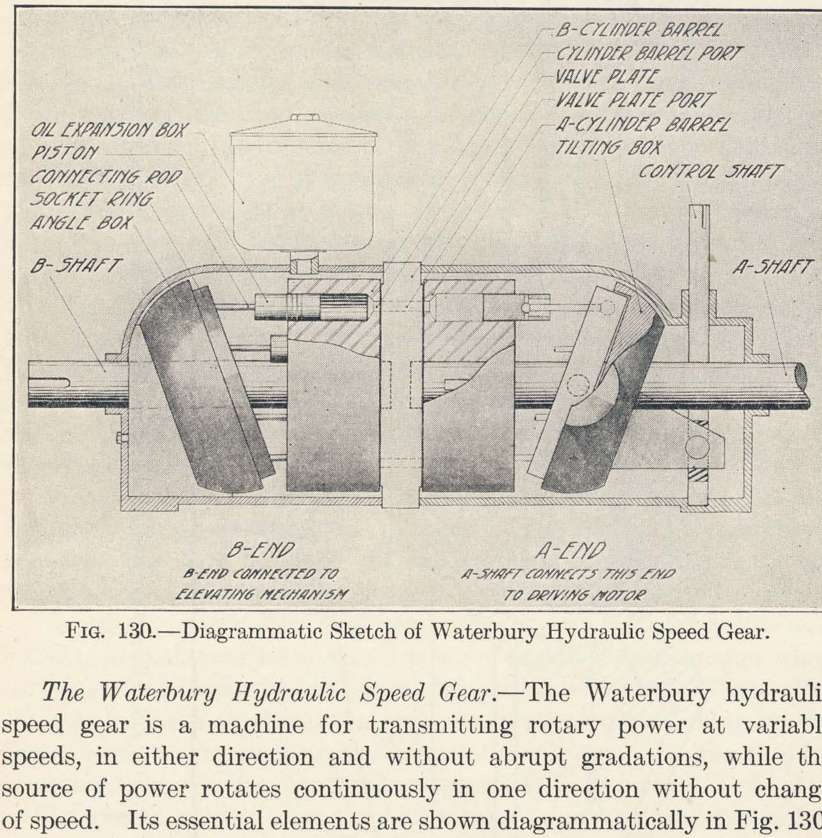


FIG. 130.—Diagrammatic Sketch of Waterbury Hydraulic Speed Gear.

The Waterbury Hydraulic Speed Gear.—The Waterbury hydraulic speed gear is a machine for transmitting rotary power at variable speeds, in either direction and without abrupt gradations, while the source of power rotates continuously in one direction without change of speed. Its essential elements are shown diagrammatically in Fig. 130.

The A-end is an oil pump operated by the driving power, generally an electric motor. The B-end is a hydraulic engine. Its shaft rotates at any speed and in either direction, depending entirely on the quantity and direction of delivery of the oil it receives from the A-end.

The entire space within the case and valve plate not actually occupied by metal is filled with oil. A definite portion of the oil is enclosed

within the cylinders ahead of the pistons and within the port passages in the valve plate. This is the active oil or oil used in transmitting energy. The remaining or inactive oil is never under pressure and serves as a supply for lubrication and for replenishment, by the operation of special valves, required on account of leakage of active oil.

The tilting box is trunnioned to the case and does not rotate with the A-shaft. It forms a guide or bearing surface for the A-socket ring which rotates with the A-shaft, to which it is fixed by a universal joint.

The socket ring has nine connecting rods fixed to it by ball joints. The inner ends of the connecting rods are fixed in the same manner to pistons which are constrained to a reciprocating motion in the nine cylinders of the cylinder barrel. The cylinder barrel is keyed to the A-shaft and its inner side bears against the fixed valve plate. The valve plate carries the inner bearing for the A-shaft. The cylinder barrel ports are interrupted annular slots cut in the cylinder barrel through which oil passes to the B-end.

The valve-plate ports are semi-annular passages cut in the valve plate, one in each half of the plate. At the top and bottom of the valve plate and between the valve-plate ports are solid portions of the plate called lands.

The B-end is the same as the A-end except that the angle box, which replaces the tilting box, is fixed in position.

To understand the operation of the speed gear, we will first assume that the A-tilting box, with its socket ring, is set at the neutral position, that is, perpendicular to the shaft. Under this condition, the shaft in rotating will carry around with it the socket ring and the cylinder barrel together with the pistons and connecting rods, but the pistons will have no tendency to reciprocate, or move to and fro in the cylinders. Therefore there will be no drawing in of the oil or forcing it out through the valve plate. The B-end will not be disturbed nor be in motion.

If the top of the tilting box now be moved away from the valve plate by the control shaft and if the A-shaft be rotating toward the observer, all the pistons, as they move up on the far side of the machine, will draw in oil through the port in the far side of the valve plate; all the pistons as they move down on the near side will slide in towards the valve plate and force the oil through the port in the near side of the valve plate. The near port will thus be under pressure while the far port is in suction.

The quantity of oil forced through the valve-plate port depends upon the length of the piston stroke and consequently upon the angle at which the tilting box is inclined.

We have spoken of forcing the oil through the valve-plate port, but this cannot take place unless there is some means of receiving the oil

and carrying it across to the port that is under suction. This is the function of the B-end. The B-socket ring is fixed in position and stands at an angle of about 70° to the B-shaft. When the B-shaft rotates, the B-pistons always will make their full stroke as they pass between the bottom and the top positions. Now, when the A-cylinders are moving down on the near side, as described above, oil is forced through the valve-plate port of this side into the B-cylinders of the near side. But they cannot receive the oil unless their pistons move back to give space. This backward movement of the pistons is communicated to the inclined socket ring through the connecting rods and causes the socket ring to rotate on its roller thrust bearing and to carry the shaft around with it. The shaft in turn rotates the cylinder barrel keyed to it, and the whole B-group rotates in the direction opposite to the rotation of the A-shaft.

The speed of rotation of the B-shaft depends upon the quantity of oil it must take care of. The B-socket ring is so set as always to give the B-pistons their full stroke. If each cylinder has a capacity of 3 cu. in., for instance, the revolving of all nine of the B-cylinders would transfer 27 cu. in. of oil from the near side to the far side. If now the control shaft of the A-end is turned so as to tilt the A-socket ring only a little, say enough to reciprocate each piston to the extent of 0.01 cu. in., all nine of the A-cylinders together will transfer, at each rotation of the shaft, 0.09 cu. in. of oil from the far side to the near side. Since the capacity of the B-cylinders for each rotation of the B-shaft is 27 cu. in., 300 rotations of the A-shaft will be necessary to rotate the B-shaft once.

If the A-socket ring is tilted further, the B-shaft must rotate proportionately faster. The speed of the B-shaft is thus dependent upon the inclination of the socket ring or, what is the same thing, the angle through which the control shaft is turned.

When the A-socket ring is tilted in the direction opposite from that shown in the figure (that is, is tilted with the top toward the valve plate) and the A-shaft still rotates in the same direction as before, the oil will be sucked in from the near port of the valve plate and forced out through the far port. This action will cause the B-shaft to rotate opposite to its former direction; that is, in the same direction as the A-shaft.

The pressure of the oil in the valve plate ports depends upon the resistance offered to the turning of the B-shaft. The pressure rises instantly to meet any resistance up to the capacity of the driving motor. If the A-socket ring stands almost perpendicular to the shaft, only a very small quantity of oil is transferred by each rotation, which has the effect of giving a very great leverage and low speed on the B-shaft.

The Waterbury hydraulic speed gear transmits rotary motion

smoothly and with such complete control as to give instantly any speed required. It is employed in the elevating, traversing, and ramming mechanisms of the 16-in. gun and carriage and of all the most recent artillery of large caliber.

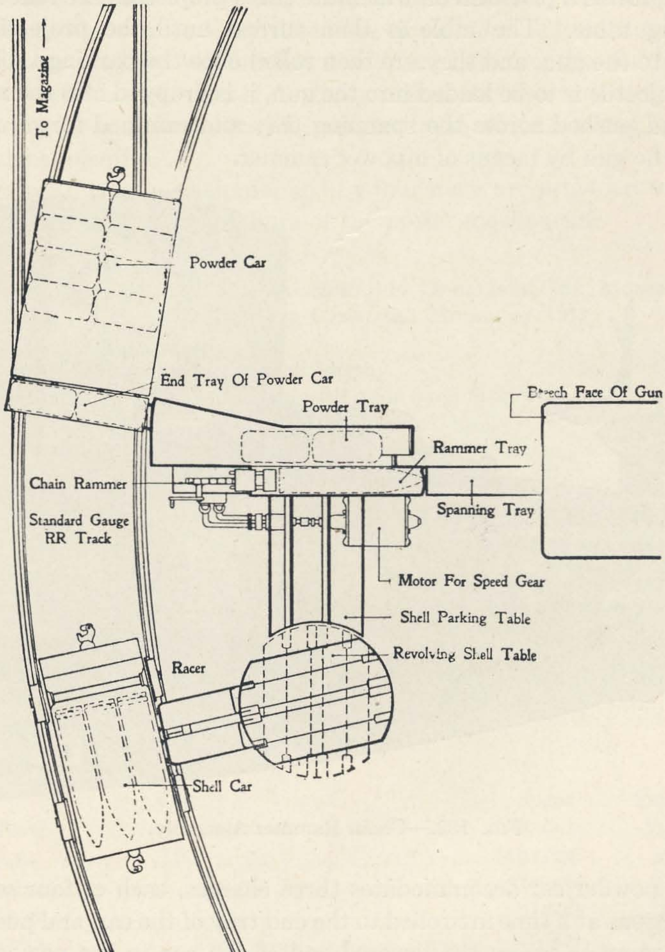


FIG. 131.—Diagram of Loading Arrangement.

Loading Arrangements.—Surrounding the mount is a standard-gage railroad track, Fig. 131, from which tangent tracks lead to the magazines. The ammunition cars are loaded at the magazine, pushed to the circular track by a power car, and then moved by hand to their positions in rear of the mount where they are attached to traversing parts of the carriage.

When the ammunition has been unloaded, the cars are uncoupled from the carriage and returned to the magazines.

The projectile car body is at the same height as the top of the revolving table; the side of the car is hinged and, when lowered to a horizontal position, forms a platform on which the three projectiles are rolled to the revolving table. The table is then turned until the projectiles are parallel to the gun, and they are then rolled onto the parking table. As each projectile is to be loaded into the gun, it is dropped into the rammer tray, and pushed across the spanning tray and rammed forward to its seat in the gun by means of a power rammer.

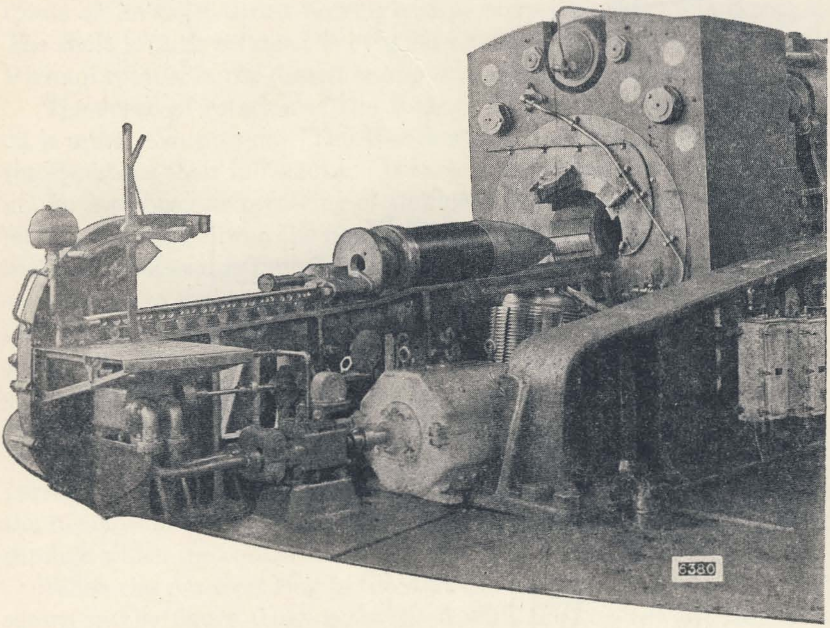


FIG. 132.—Chain Rammer Assembly.

The powder car accommodates three charges, each of four sections. Two sections at a time are rolled to the end tray of the car, and pushed by a hand rammer across the lowered end of the car to the powder tray. When the projectile has been seated, the two sections are rolled onto the rammer tray and are then pushed into the powder chamber by the power rammer. The remaining two sections of the charge are then brought from the powder car and loaded similarly.

Power loading was adopted for this mount to increase the rapidity of fire, and to insure uniform seating of the heavy projectile. The power rammer assembly is attached to the racer immediately in rear of the

gun. (Fig. 132). It comprises a cast steel frame, on the top of which is a rammer tray, and a flexible non-buckling steel chain which is driven by a sprocket and, in turn, is driven by an electric motor through a hydraulic speed gear. The part of the rammer chain below the tray and sprocket is coiled inside the frame. A hydraulic rammer head is attached to the front of the chain to take up the shock of starting and seating the projectile. A spanning tray bridges the space between the rammer tray and the breech of the gun. As the sprocket is revolved, the chain is pulled over it and the hydraulic rammer head at its forward end rams home the projectile.

Two hand cranks, each manned by four men, are provided to permit manual loading in case of failure of the power mechanism.

MISCELLANEOUS DATA PERTAINING TO THE 16-IN. 50-CALIBER GUN, MODEL OF 1919, MII, AND BARBETTE CARRIAGE, MODEL OF 1919.

Gun, wire-wound, approximate overall length	70 ft.
Weight of gun and breech mechanism with recoil band filled with lead	385,800 lb.
Weight of gun	326,600 lb.
Weight of recoiling parts	399,900 lb.
Weight of tipping parts	499,200 lb.
Weight of projectile	2,340 lb.
Weight of powder charge	832 lb.
Total dead weight that comes on foundation	1,000,000 lb.
Total trunnion pull at 65° elevation	1,650,000 lb.
Weights of principal castings as delivered from foundry (no machining):	
Base ring, 4 sections, each section	21 tons
Racer, 4 sections, each section	25 tons
Cradle	51 tons
Side frames (2), each	17 tons

Weights of forgings and ingots:

Part	Ingot, Pounds	Forging, Pounds
A-tube	194,000	48,500
B-tube	276,000	69,000
C-hoop	91,500	22,800
D-hoop	315,500	79,000
E-hoop	162,500	40,600
Jacket	123,500	30,800
Breechblock	10,700	2,700

Travel of projectile	675.22 in.
Volume of powder chamber	40,900 cu. in.
Density of loading	0.5882
Maximum pressure	38,000 lb. sq. in.
Muzzle velocity	2,700 ft.-sec.
Muzzle energy	118,400 ft.-long tons

Force required to pull gun into recoiled position against the compressed air in the recuperator	800,000 lb.
Electric power:	
Traversing motor	7.5 h.p.
Elevating motor	50 h.p.
Air compressor motor	30 h.p.
Rammer motor	30 h.p.
Total power of motors	117.5 h.p.

242. The 16-in. Howitzer, Model 1920, on Barbette Carriage, Model 1920.—(Fig. 133.) The decision to build and install in the harbor defenses fixed primary armament of this type was based on the effective performance of large-caliber howitzers during the World War. Although only a small number of these howitzers and mounts were constructed and emplaced, and they are not standard armament for future harbor

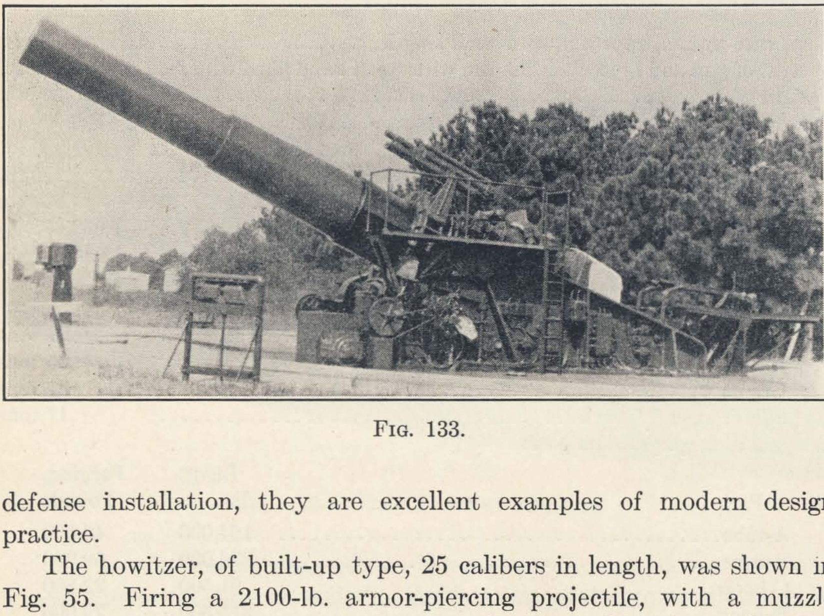


FIG. 133.

defense installation, they are excellent examples of modern design practice.

The howitzer, of built-up type, 25 calibers in length, was shown in Fig. 55. Firing a 2100-lb. armor-piercing projectile, with a muzzle velocity of 1950 f. s., a maximum range of 24,500 yd. is obtained. The breech and firing mechanisms are identical in construction and operation to those utilized on the 16-in. gun just described.

The carriage permits all-around fire, at elevations between $-7°$ and $+65°$. The base ring, rollers, racer, side frames, cradle, elevating mechanism, traversing mechanism, and loading arrangements do not differ materially from the corresponding parts of the 16-in. Barbette Carriage, Model 1919, just described. However, because of the de-

creased weight and power of the howitzer, the carriage parts may be made lighter and simpler.

The recoil brake consists of 4 hydraulic cylinders of the same type as the 2 short recoil cylinders of the Model 1919 carriage. They incorporate counter-recoil buffers of the dashpot type in place of the special buffers provided at one end of the long cylinders in the Model 1919 carriage; this simple buffer may be used because of the greatly reduced weight of the recoiling parts, which permits employment of greatly reduced recuperating effort. The recuperator mechanism is of the pneumatic type, similar to that of the Model 1919 carriage, but comprising one cylinder only, mounted in a bracket at the bottom of the cradle.

Figure 133 shows the 75-mm. Subcaliber Mount M3, on the howitzer. This typifies the modern practice of exterior mounting of subcaliber equipment, which has superseded the old practice of installing subcaliber tubes within the bores of the major weapons.

243. The 12-in. Gun, Model 1895, MI, on Barbette Carriage, Model 1917.—A considerable number of these carriages have been

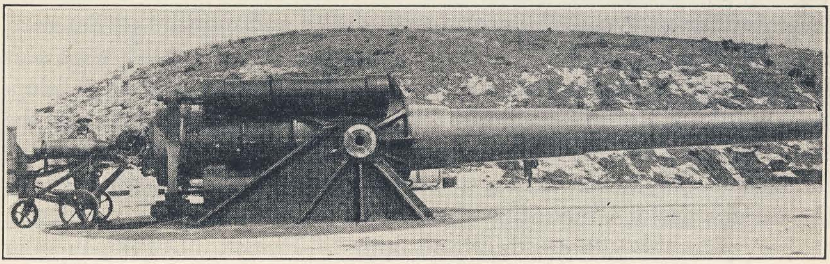


FIG. 134.—12-in. Gun on Barbette Carriage, Model 1917.

constructed and emplaced. They permit all-around fire, at elevations between 0° and 35°. They are simple, well-designed carriages, utilizing electric power through a Waterbury hydraulic speed gear for elevating the gun, and floating trunnions to reduce friction.

The base ring, rollers, and racer are of a design similar to those already described. The simple side frames and the cradle are well illustrated in Fig. 134. A single recoil cylinder, of hydraulic type, is employed, mounted on the bottom of the cradle. The counter-recoil buffer is of the dashpot type, at the front end of the recoil cylinder. The recuperator mechanism is of the spring type, four cylinders being employed, located above and below the cradle on each side. Each cylinder comprises three concentric columns of helical springs, each column being divided longitudinally into four sections.

The 12-in. gun is of the built-up type, consisting of a tube, jacket, and eight hoops. It is similar in shape, weight, and dimensions to the 12-in. Gun, Model 1888, illustrated in Fig. 55, except that the 16 hoops of the latter were consolidated into 8. The gun fires a 1070-lb. projectile, at a muzzle velocity of 2250 f. s., attaining a maximum range of 27,600 yd. The full range potentialities of the gun cannot be realized because of the 35° maximum elevation permitted by the carriage. The gun employs the old type of slotted-screw breech mechanism, Fig. 77, and the Model 1903 firing mechanism illustrated in Fig. 89.

The range and elevation of this gun and mount are only half, approximately, of those of the 16-in. gun and mount previously described, but it was the most modern armament in the harbor defenses until the latter weapon was provided. It still remains a valuable defensive weapon. The illustration shows a modern type of emplacement, without parapet of any kind, and with the operating mechanisms below the platform.

RAILWAY ARTILLERY

The earliest recorded use of railway artillery was during the American Civil War. Both the Union and the Confederate Armies mounted several different types of muzzle-loading guns and mortars on flat cars, armored with railway iron. Several nations experimented with this type of artillery during the next 50 years, but there was little development until 1914. The demands for heavy artillery of all types in the World War led to very rapid development of railway artillery, designed for field employment. Many types of carriages were constructed by the various nations, mounting guns, howitzers, and mortars, varying in caliber up to the 520-mm. howitzer built by France. Development or design by the United States during this period provided mounts for guns to include 14-in., 12-in. mortars, and 12-in. and 16-in. howitzers. A great deal of this matériel is still available for emergency use; design was continued after the war and standard mounts are now available.

Railway mounts are classified, according to the recoil system employed, as *sliding mounts*, *rolling mounts*, and *platform mounts*. In the *sliding mount*, the car body is jacked down in firing until the wooden crossbeams underneath rest on steel I-beams installed parallel to the rails, transferring a large part of the weight from the car trucks. The entire mount slides to the rear in recoil, the recoil energy being absorbed by sliding friction. This type of mount may be non-traversing, or the entire car body may be traversed a few degrees on its trucks. It is fired from a curved track or *epi*, so laid out as to permit the desired pointing in azimuth.

The *rolling mount* rolls backward in recoil, on its own wheels, on

standard track, the hand brakes being set to absorb part of the recoil energy. The gun is usually mounted in a cradle, with recoil cylinders which also absorb a part of the energy. Although usually designed for car traverse, permitting a few degrees movement in azimuth, the mount is fired from an epi.

The *platform mount* is the most important type. It is equipped with a recoil system to absorb the energy of recoil, and remains in place without movement. The necessary anchorage is provided by a special ground platform, and/or by use of outriggers. Certain types are designed to fire from prepared concrete emplacements, becoming, in effect, fixed artillery. Platform mounts are designed for top-carriage traverse, similar to that employed in fixed mounts, varying with the particular design from 7° to 360°. Modern post-war mounts are of this type. They are suitable both for harbor defense and field use. No sliding or rolling mounts are in service at this time.

The standard harbor and seacoast defense railway artillery of the United States service comprises a 14-in. gun railway mount for the primary armament and an 8-in. gun railway mount for the secondary armament.

244. The 14-in. Gun Railway Mount, Model 1920.—This unit mounts the 14-in. Gun, Model 1920 MII, 50 calibers in length, firing a 1560-lb. armor-piercing projectile, at a muzzle velocity of 2650 f. s., to a maximum range of 42,280 yd. The breech mechanism of the Welin type and the firing lock have already been described in Chapter VI. The mount permits gun elevations from $-7°$ to $+50°$. It can be fired from a temporary or field emplacement, 7° traverse of the top carriage being provided, or from a prepared fixed emplacement permitting 360° traverse. A gasoline-electric unit supplies necessary power for operating the elevating, traversing, top carriage lifting, and mount lifting mechanisms. The arrangement for lifting and lowering the top carriage is to permit attainment of necessary railway clearance in traveling. The mount lifting and lowering mechanism is provided to lower the mount at the emplacement and to raise it for travel.

For field and seacoast defense use, the mount may be fired from specially constructed curved tracks or epis, the locations of which are based on strategic and tactical considerations. Standard track is used, with heavy rock-ballasted ties, and with steel I-beams spiked to the ties parallel to the rails. The gun is laid in direction by movement of the mount along the epi, and by the $3\frac{1}{2}°$ traverse on each side of the normal provided by the top carriage. The construction of the mount permits the entire car body to be lowered until the weight is borne by the I-beams. Additional support in firing is afforded by the rear trucks and

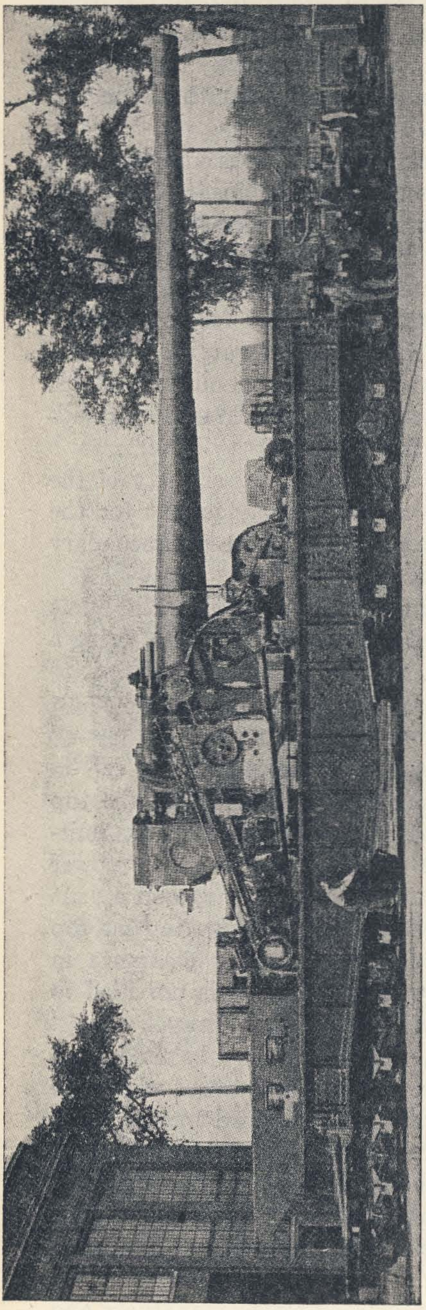


FIG. 135.—14-in. Railway Mount, Model 1920. In Firing Position.

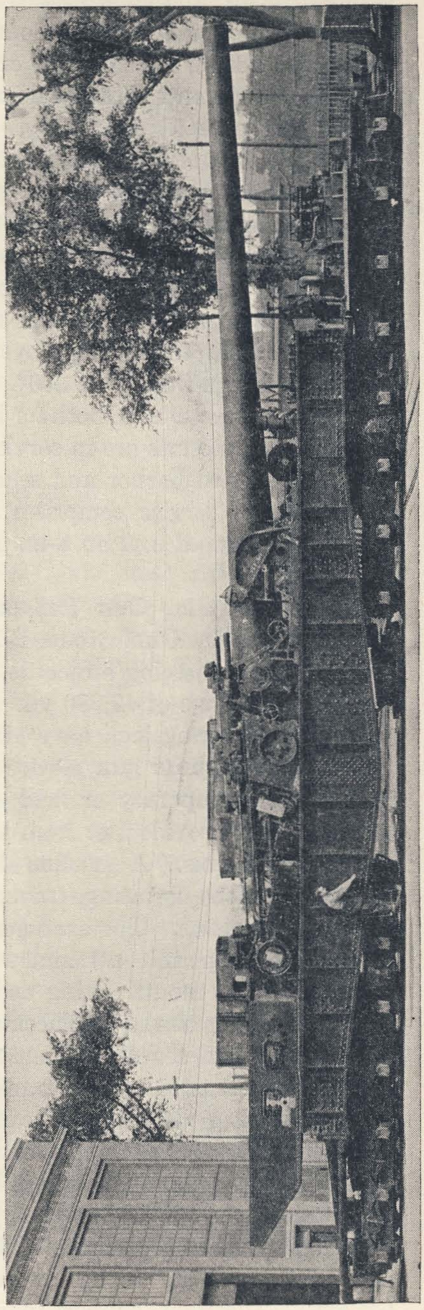


FIG. 136.—14-in. Railway Mount, Model 1920. In Traveling Position.

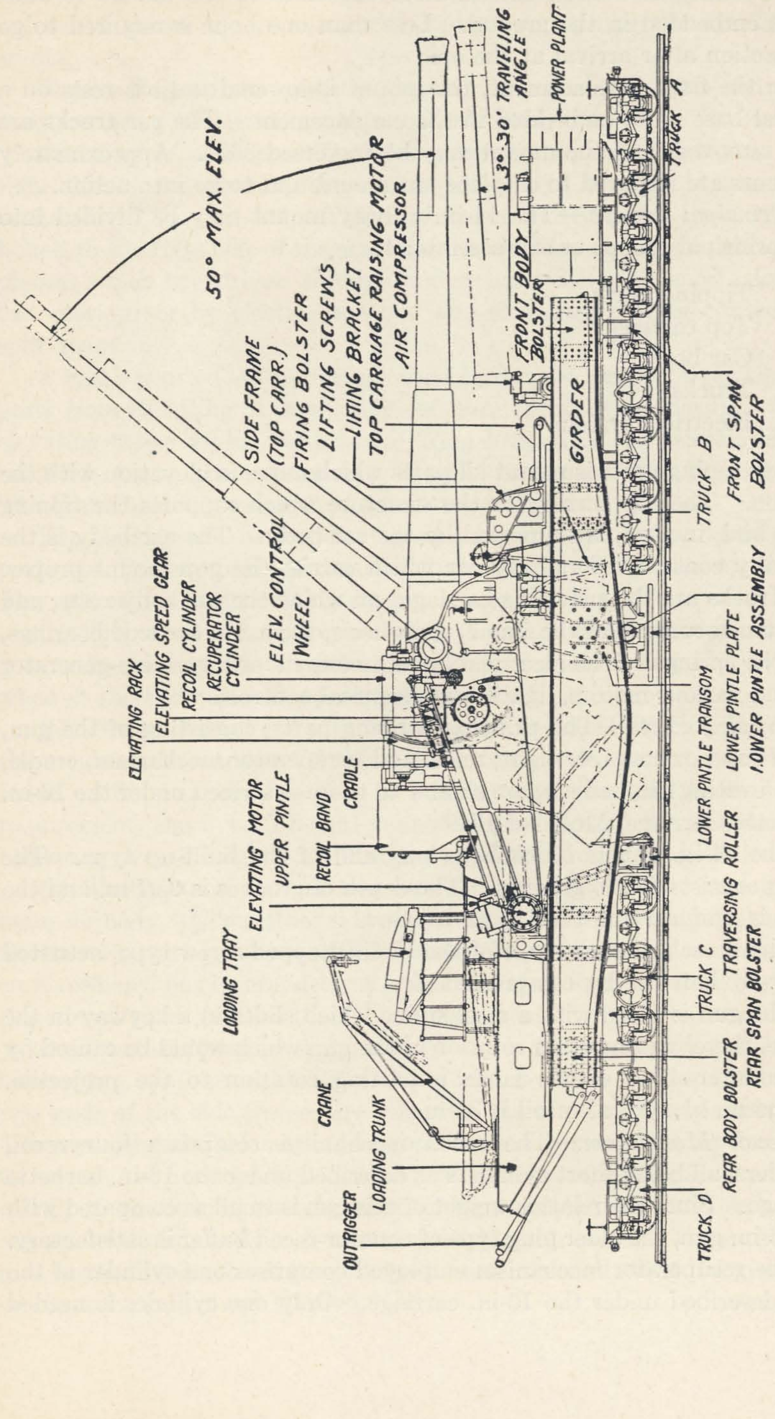


Fig. 137.—14-in. Gun and Railway Mount, Model 1920. Nomenclature and Details.

by six outriggers which extend from the sides of the mount to steel floats embedded in the ground. Less than one hour is required to go into action after arrival at the epi.

In the fixed emplacement, the mount is lowered until it rests on a central base plate embedded in the emplacement. The car trucks are then removed, and the mount may be traversed 360°. Approximately $2\frac{1}{2}$ hours are required to emplace the mount and to go into action.

Principal Groups.—The 14-in. railway mount may be divided into five principal groups or sub-assemblies:

Tipping parts.
Top carriage.
Car body.
Trucks.
Electrical system.

By tipping parts is meant all parts which move in elevation with the cannon. The top carriage is the structure which supports the tipping parts and, in turn, is supported by the car body. The car body is the specially constructed railway car which carries the gun mount proper. The trucks are the swiveling carriages on which the car body rests, and each truck consists of the frame, the wheels, the axles, the axle bearings, and the springs. The electrical system consists of a gasoline-generator set and various motors, lights, and electrical controls.

Tipping Parts.—The principal tipping parts, consisting of the gun, recoil band or counterweight, recoil and recuperator mechanism, cradle, and elevating mechanism, are similar to those described under the 16-in. Barbette Carriage, Model of 1919.

The 14-in. gun is 50 calibers long and of the built-up type. The rifling consists of 126 grooves. The depth of grooves is 0.07 in. and the twist is uniform one turn in 32 calibers.

The breech mechanism is of the Welin stepped-screw type, actuated either by hand or by compressed air.

The gun is fitted with a steel spline which slides in a keyway in the cradle, thereby preventing rotation of the gun which would be caused by the counter-effect of the lands imparting rotation to the projectile. The normal length of recoil is 35 in.

Recoil Mechanism.—The recoil mechanism comprises four recoil cylinders, all being short cylinders as described under the 16-in. barbette carriage. Since the relative weight of this gun is small as compared with the 16-in. gun, the older plug type of counter-recoil buffer is satisfactory.

The recuperator mechanism employed comprises one cylinder of the type described under the 16-in. carriage. Only one cylinder is needed

because of the decreased weight of the recoiling parts. The cylinder is located above and in the vertical plane containing the axis of the cradle.

The cradle is of the gridiron construction and carries one elevating rack providing for elevations between $-7°$ and $+50°$.

Elevating Mechanism.—The elevating mechanism, located on the right side of the carriage, elevates and depresses the gun between the limits of $-7°$ and $+50°$. The mechanism consists of a rack, rigidly bolted to the right side of the cradle, in which there engage two elevating pinions which are driven through a gear train either by hand (slow or fast motion) or by electric power. The elevating gearing consists of spur gears only.

A brake is provided to prevent the unbalanced weight of the tipping parts from elevating or depressing the gun, except when desired. The elevating brake consists of a brake drum located on the outside of the right side frame, the outer surface of which is engaged by a brake band. The brake is always on, except when it is released by hand.

Top Carriage.—The top carriage is a heavy, steel frame which supports the tipping parts and is, in turn, supported by the car body. The reasons for incorporating a top carriage are:

(*a*) The trunnions are supported at a height which will permit the gun to be fired at the maximum elevation and still allow the breech, when at the end of recoil, to clear the roadbed.

(*b*) The cradle and gun may be lowered to a height which will permit the mount to be transported through the tunnels and across the bridges found on the principal railroads in this country. In order to meet this requirement, the overall height cannot exceed 14 ft. 5 in., whereas the necessary overall height to permit the condition under (*a*) is 20 ft.

(*c*) The gun and top carriage may be traversed, with respect to the main car body, $3\frac{1}{2}°$ on either side of normal. The traversing mechanism for the top carriage is not utilized when the mount is on a permanent emplacement, but is intended for correction of azimuth when firing from the curved track (*epi*) of the field emplacement.

Construction Details.—An assembly of side frames, pintle, traversing mechanism, and other details of the mount is shown in Fig. 138. The rear ends of the side frames are joined to the main car body through a universal joint. This method of construction permits the top carriage to rotate in a horizontal plane about this joint, or *upper pintle* as it is called, thus allowing the top carriage and gun to be traversed with respect to the car body. It also permits the top carriage to be rotated in a vertical plane about the joint as an axis, thus allowing the gun and cradle to be raised and lowered.

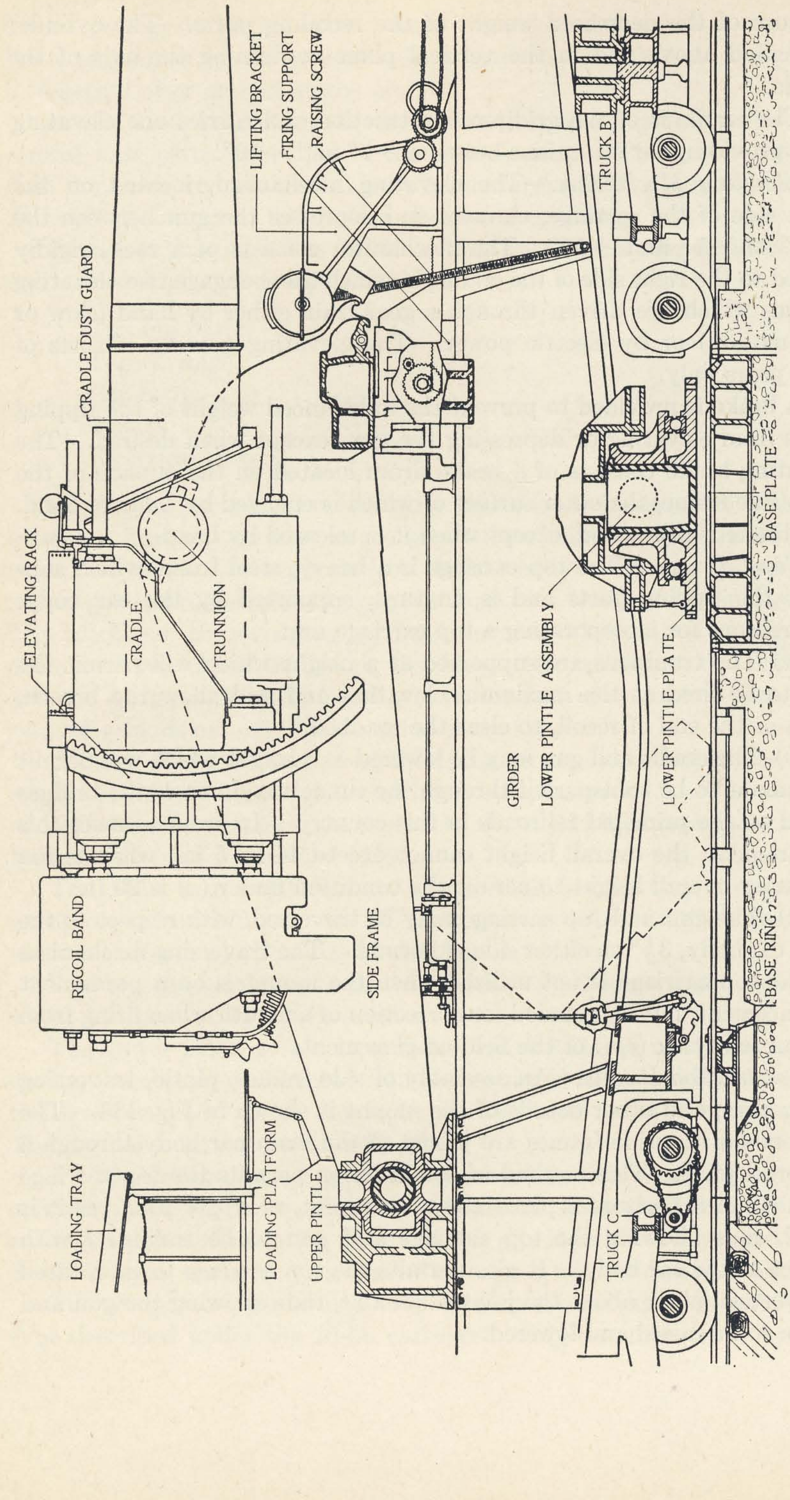


Fig. 138.—14-in. Gun and Railway Mount. Details.

When in the firing position, the front end of the top carriage is supported by the *firing support*, a heavy beam extending across the top of the main car girders. It can be moved a limited distance along the girders by means of hand-driven pinions, but is provided with clips to prevent any other movement.

In the bottom of the front end of each side frame of the top carriage is a traversing roller. The traversing rollers, two in number, are mounted in adjustable yokes which are supported through Belleville springs. The top surface of the firing support forms the path for these rollers. The rollers are adjusted so that the bottom of the front end of the top carriage is lifted about 0.02 in. above the top of the firing support. When these rollers are subjected to the firing load, the Belleville springs are compressed and the side frames rest directly on the heavy firing support. When the firing load is removed, the Belleville springs raise the side frames from the firing support, so that they are again carried on the rollers. The principle of construction employed in this mechanism is very similar to that of the antifriction device used for reducing the friction at the main trunnion bearings. The mechanism permits the top carriage to be supported by roller bearings for traversing, but does not require the use of a sufficient number of rollers to withstand the excessive load encountered when the gun is fired.

To lower the top carriage from the firing to the traveling position, the top carriage is raised by means of a lifting mechanism, which is described in a subsequent paragraph, until its weight is no longer supported by the firing support. The firing support then is run forward until it is clear of the front end of the top carriage. The front end of the top carriage is then lowered between the main car girders until its weight is resting on a transom extending across the car body at the lower edge of the girders. When the top carriage is in this position, the mount has proper railway clearance for travel on all the principal railroads of the United States and for passing all mainline cuts, bridges, and tunnels.

Top Carriage Lifting Mechanism.—For changing the top carriage, cannon, and cradle from the traveling position to the firing position, or vice versa, there is provided a mechanism consisting essentially of two lifting brackets which carry the raising screws, Fig. 139. The brackets are located directly in front of the top carriage side frames, and are supported by the car girders through an intermediate transom and platform which rests on top of the girders. A raising screw extends from each bracket downward. An eye is formed at the lower end of each screw, and a cross rod passes through these eyes, thus connecting the screws at their lower ends. This cross rod engages in the hooks on the front of the side frames.

The top of each lifting bracket forms a yoke for supporting the raising-screw nut housing by its trunnions. In each housing is a heavy nut supported by roller bearings and rotated by the raising-screw gears which are driven either by hand or by power. When these nuts are revolved, the raising screws move up or down and raise or lower the top carriage. Since the lower ends of the screws, which engage with the side frames, move on the arc of a circle, the screws will oscillate in raising or lowering the top carriage. The raising-screw nut housings rotate

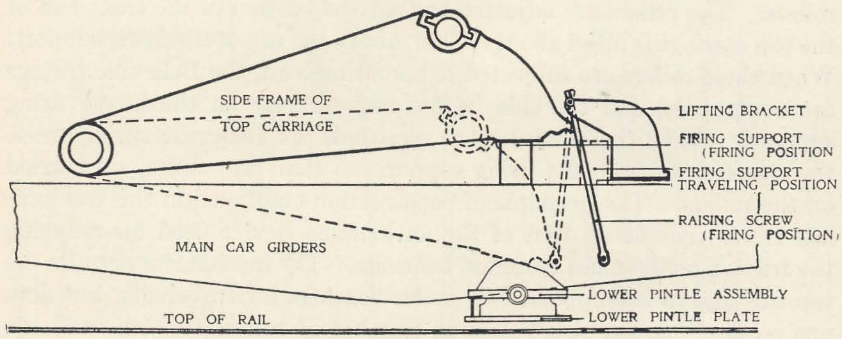


FIG. 139.—Top Carriage Lifting Mechanism.

about their trunnions permitting this action. The weight lifted by the two screws is approximately 280,000 lb.

After the top carriage has been raised to the firing position and the firing support placed under the front end of the side frames, the raising screws are run down out of the way.

While the car is in travel, the screws are left engaged with the side frames but the tension on the screws is relieved.

Car Body. (Fig. 137).—The car body consists essentially of two silicon steel girders, joined together at the front and rear by heavy body bolsters and intermediate transoms in order to obtain the desired stiffness. The heavy body bolsters are U-shaped in longitudinal cross section, the U opening downward. Inside of this U fits another bolster known as the lifting bolster. Forward of the geometrical center of the main car body, and extending beyond the lower edges of the girders, is the lower pintle transom. Mounted on top of and extending beyond the rear of the girders is the loading trunk. The loading trunk is constructed like a steel box, in which are mounted the various speed gears and mechanisms for operating the ammunition hoists and rear mount-raising mechanism. The top of the loading trunk forms the loading platform.

Mount-lowering Mechansim.—For lowering the mount when it is being emplaced, there is a lifting bolster (at each end of the car body) which rests on the span bolster of the railway trucks and, through two screws, supports the heavy body bolster, Fig. 140. On the under side of this lifting bolster is a pintle which fits in an annular recess in the top of the span bolster on the trucks. There are two vertical screws which screw through the lifting bolster and extend up through the aligning beam. These screws are provided with collars near their upper ends so that there can be no up and down motion of the screws with respect to the aligning beam. There is no vertical movement between the aligning beam and the body bolster. A large spur gear attached to the top of each screw meshes with a pinion driven by hand or through the speed gear; thus the screws are rotated and the lifting bolster raised or lowered. Metal wedges are inserted over the journal bearing boxes before the bolster is raised.

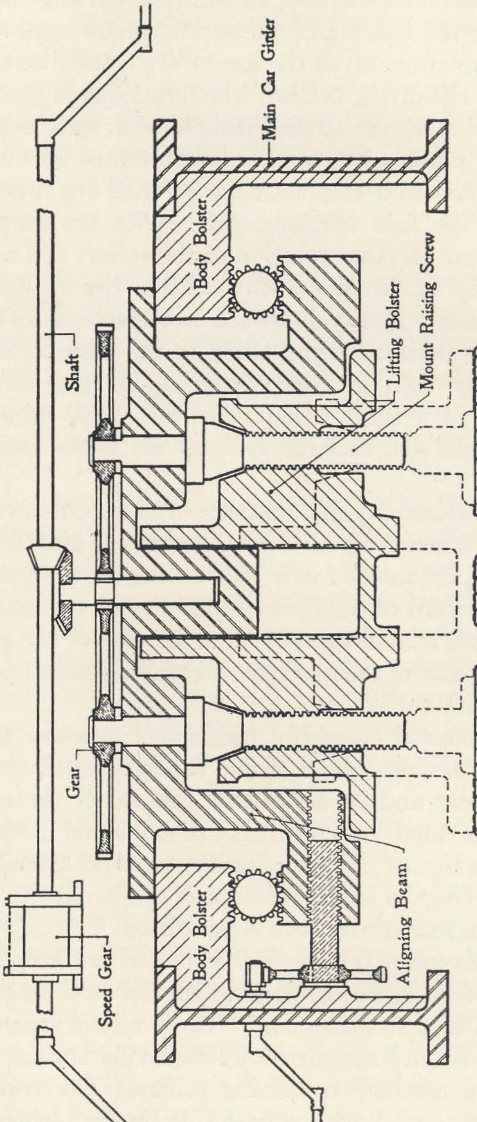


FIG. 140.—Mount-lowering Mechanism (Schematic).

Until the mount reaches the emplacement, the lifting bolster at each end is at its lower position (shown by dotted outline in figure), supported by the span bolsters, and, in turn, supporting the entire weight of the mount by the bearing of the screw collars against the aligning beams. At the emplacement, as the screws are rotated so that they travel downward into the lifting bolster, which remains in place, the entire mount is lowered with respect to the lifting bolster, span bolster, and trucks, until the lower pintle plate of the mount comes into contact with the base plate of the fixed emplacement or with the I-beams adjacent to the tracks in the field emplacement. With the mount supported by the emplacement, further rotation of the screws will not result in their continued axial movement downward into the lifting bolster; instead, the lifting bolster will travel upward on the screws, as would a nut on a bolt. The lifting bolster is thus raised to the position shown in Fig. 140, the trucks may then be rolled from under the car, and the mount is emplaced as a fixed mount. In the field emplacement, the trucks are not removed, and the rear set of trucks assists in supporting the mount.

Mount-traversing Mechanism.—The mount-traversing mechanism is employed when the gun is on a permanent emplacement. It comprises a pedestal, trunnioned in a yoke swung between the main car girders at a point forward of the center of gravity of the mount; and a traversing beam which is attached to the under side of the girders 16 ft. $2\frac{1}{4}$ in. in rear of the axis of the pedestal. This mechanism permits a 360° traverse of the entire car body.

The pedestal assembly consists of a lower pintle plate, which is bolted to the base plate of the concrete emplacement; and the lower pintle proper and its bearings. Instead of the conical roller bearings usually provided, ball bearings are employed in the traversing mechanism of this mount. By having the pedestal assembly trunnioned to the main car body, a slight rotation of the mount in a vertical plane containing the axis of the bore is permitted.

The traversing beam, which is bolted to the under side of the girders, contains two traversing rollers which rest on the steel base ring embedded in the concrete emplacement. These rollers are mounted in adjustable yokes, which are supported by Belleville springs in the same manner as the top carriage traversing rollers. The traversing beam is held a short distance above the base ring by the springs and rollers until the firing load compresses the springs and allows the beam to rest directly on the base ring. By this means, easy traversing is provided but the full firing load is supported by the pedestal and traversing beam of the mount and the steel plate and base ring of the fixed emplacement. On

discharge of the gun there is a slight rotation of the mount about the lower pintle trunnion.

The mount is traversed on the rollers, which are driven through a traversing mechanism comprising shafts and spur gears leading to the traversing speed gear and hand cranks.

Permanent Emplacement.—To obtain the most effective fire, especially when it is desired to use this mount against moving targets or to transfer the fire rapidly from one target to another, the mount is put on a fixed or permanent emplacement. The fixed emplacement consists of a base ring and base plate bolted to a concrete block 42 ft. in diameter.

In the center of the concrete base there is a cylindrical depression $9\frac{1}{2}$ ft. in diameter and $11\frac{1}{2}$ in. deep, in which is placed the base plate. The necessary foundation bolts are placed in the concrete when it is poured. The base plate is a heavy steel casting made in one piece, and is in the form of a hollow ring. This plate is lowered into the central depression of the concrete base, leveled, and permanently bolted to the concrete.

The base ring is a heavy steel ring made in six sections, bolted together. This ring forms the path upon which the mount-traversing rollers move. The roller path is approximately 15 in. wide, and 32 ft. $4\frac{1}{2}$ in. in diameter. It is bolted on top of the concrete base concentric with the base plate. On the inside of this ring there is a flange or clip surface, under which the clip on the traversing beam engages.

Fastened on the outside of this ring is an azimuth circle which is used in indirect fire. The azimuth pointer is attached to a folding platform on the left side of the mount at the end of the mount-traversing beam.

A standard railroad track is laid up to the concrete base, ending normal to the circular base on one side and continuing from the other side at a point diametrically opposite. There is a space from the end of the main track to the base ring (about 3 ft.) which is bridged on either side by means of four special rails, known as bridge rails. These rails are bolted to the concrete base and the base ring. Extending from the inner radius of the base ring to the base plate on either side are four additional special rails, known as hinge rails. Cast integral with the base plate are two rails extending across it, which meet with the hinge rails. These various rails form a continuous track which runs across the center of the emplacement, and on which the mount can be moved.

Mounting on Permanent Emplacement.—The car mount is pushed on the emplacement until the lower pintle plate is nearly central over the base plate. The lower pintle lock is disengaged, the two rear

bridge rails are removed, and the two hinged rails are swung into the recess provided in the emplacement.

The mount is then lowered by means of the mount-lowering device described, until the lower pintle plate is just above the base plate of the emplacement.

When the lower pintle plate is centered over the base plate, the mount is lowered until its weight rests on the base plate. The lower pintle plate is then bolted down solidly, and the mount-traversing clip on the under side of the mount-traversing beam is engaged under the clip surface of the base ring.

The top carriage is then raised to the firing position, the firing support run underneath it, and the raising screws run down as far as they will go.

Now the trucks are run from under the mount. The rear trucks may be moved any desired distance, but the front trucks, carrying the power plant, must not be moved more than 100 yd., as this is the length of cable supplied to connect the power plant with the mount.

The ammunition cranes and other small components are set up and the mount is ready for firing. The total time required for emplacing the mount is about $2\frac{1}{2}$ hours.

Trucks.—The trucks are designated *A*, *B*, *C*, and *D*, in order from front to rear. Trucks *A* and *B* support a large casting, shaped like an I-beam and designated as the front span bolster. On the top and in the center of this span bolster is a recess to receive the pintle on the lower side of the front lifting bolster. In addition to supporting the front end of the car body, the forward half of the front span bolster carries the power plant and its auxiliaries. Trucks *C* and *D* support a similar casting known as the rear span bolster on which the rear end of the car body rests.

Trucks *B* and *C* are each equipped with a mechanism, known as the hand translating mechanism, for moving the mount backward and forward on the track. Each mechanism consists of a hand crank which is located on the outside of the truck frame and is connected through spur gears to a sprocket wheel on the inside of the truck frame. A second sprocket wheel is mounted, through a clutch, on the truck wheel axle and can be disengaged. A roller chain, similar to a bicycle chain, joins these two sprockets.

The Loading Group.—Mounted on top of the loading platform or loading trunk are the loading cranes, loading tray, and spanning tray. There are two cranes, one for powder and one for projectiles. The cranes are so constructed that they can be taken apart and laid down on the loading platform during railroad travel.

The loading tray is mounted in rear of the breech of the gun and is

inclined downward at an angle of 7°. A shell stop is provided to prevent the shell from sliding off until the spanning tray, which connects the loading tray with the breech of the gun, is in the loading position. The spanning tray is practically the same as the one described under the 16-in. barbette mount.

The loading of the gun is by hand or, more properly, by gravity. For loading, the gun is depressed to $-7°$ and the spanning tray is placed between the breech of the gun and the loading tray. A slight impetus will start the projectile down the tray and, with its velocity increased by gravity, embeds the rotating band so firmly in the rifling that the gun may be safely elevated to the maximum elevation without danger of the shell slipping backward. A short hand rammer is used to facilitate the more sluggish movement of powder bags down the tray.

Electrical System.—Located on the front span bolster is the power plant for supplying electricity for motors, air compressor, and lights. The plant consists of a 6-cylinder gasoline engine connected to a direct-current generator with an output of 50 kilowatts at 125 volts. The generator is connected to a switchboard equipped with the necessary controls and protective appliances. Connecting the switchboard with the mount are the necessary conductor cables.

Power Distribution.—Power is distributed through motors and Waterbury hydraulic speed gears as follows:

40-hp. motor	Top carriage raising
	Mount lifting
	Mount traversing
20-hp. motor	Elevating
15-hp. motor	Loading

Air Compressor.—A 20-hp. motor is coupled direct to the 2-stage, 3-cylinder, air-cooled air compressor. The air compressor feeds into a storage tank in which the air is compressed to 175 lb. per sq. in. The tank furnishes the compressed air for operating the breechblock (which requires a pressure of only 30 lb. per sq. in.) and for ejecting the powder gases from the bore after firing.

General Data

Total traveling weight	750,000 lb.
Total weight of tipping parts	300,000 lb.
Overall length of mount	80 ft.
Muzzle energy	76,000 ft.-long tons
Trunnion pull at 50° elevation	1,000,000 lb.
Service pressure in recoil cylinders	3,800 lb. per sq. in.
Initial and final pressures in recuperator cylinders	1,800 to 2,800 lb. per sq. in.
Time to traverse 360° on fixed emplacement	3 minutes

245. The 8-in. Gun Railway Mount, M1.—This mount is designed for firing from a track emplacement. (Fig. 141.) By means of hand-operated jacks it may be raised so that I-beams can be placed on the cross ties adjacent to the rails. The car is then lowered until it rests on these beams. The trucks are not removed but do not support any

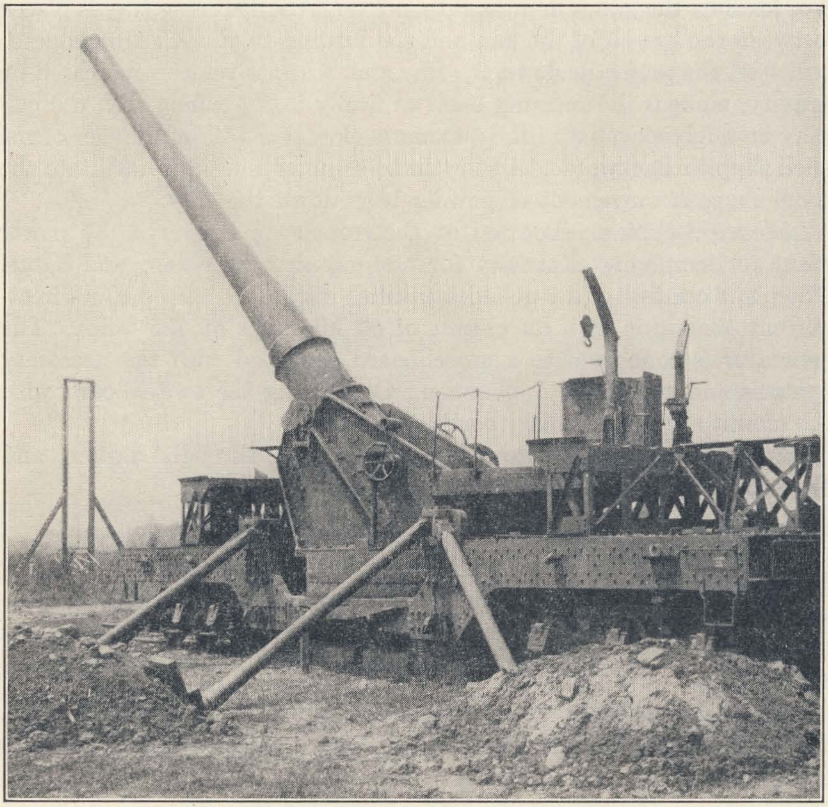


FIG. 141.—8-in. Gun Railway Mount, M1.

of the weight of the mount. The outriggers, four on each side, prevent displacement during firing.

The base ring is a steel casting rigidly riveted to the car girders, and forms an integral part of the car body. The traversing parts of the mount include the conical rollers, racer, side frames, loading platform, loading stand, and cranes. The tipping parts (gun and cradle) are supported in trunnion bearings near the front of the side frames, to permit the gun to recoil into the fairly small circular well in the racer and base

plate. A heavy counterweight near the breech of the gun permits its mounting well forward in the cradle.

The recoil system comprises two hydraulic recoil cylinders and a single pneumatic recuperator, similar to those previously described. The normal length of recoil is 27 in.

The elevating and traversing mechanisms are of the spur gear type, actuated by handwheels; a brake band and drum are provided in the elevating mechanism to hold the tipping parts in position at any elevation.

The gun is a built-up type, 45 calibers in length. Firing a 260-lb. projectile, with a muzzle velocity of 2750 f. s., the maximum range is 27,550 yd. A range of 33,850 yd. may be obtained with a 200-lb. projectile. The mount permits firing at elevations between 0° and +45°, and 360° traverse.

For loading, the gun is depressed to −5°. The projectile moves by gravity along a spanning tray, placed between the loading stand and the breech, and seats itself.

ANTIAIRCRAFT ARTILLERY

FIXED MOUNTS

246. The 105-mm. Antiaircraft Gun Mount M1.—The 105-mm. Gun, M1, on this mount, is of monobloc construction, 60 calibers in length, with a screwed-on breech ring at the rear end to support the breech mechanism. The breechblock is a vertical sliding type, opened automatically during counter-recoil, and closed automatically when the round is inserted in the gun. Owing to the heavy weight of the fixed round, a mechanical rammer, actuated by air compressed during the movement of the gun in recoil, is provided to facilitate the loading operation. The sustained rate of fire is 15 to 20 rounds per minute, which can be increased to 30 rounds for short firing periods. The gun fires a 33-lb. projectile, at a muzzle velocity of 2800 f. s., attaining maximum horizontal and vertical ranges of 20,000 yd. and 14,000 yd., respectively.

Figure 142 shows the base plate (*A*), the roller assembly (*B*), and the traversing rack (*C*). A pinion meshed with the gear (*D*) transmits to the azimuth data receiver on the mount above the present azimuth of the mount. The raised center section of the base plate serves as a pintle for the racer and to transmit the horizontal components of the firing stresses.

Figure 143 shows the racer (*A*), the pedestal (*B*) consisting of two yokes bolted together, the traversing handwheels (*C*) which are con-

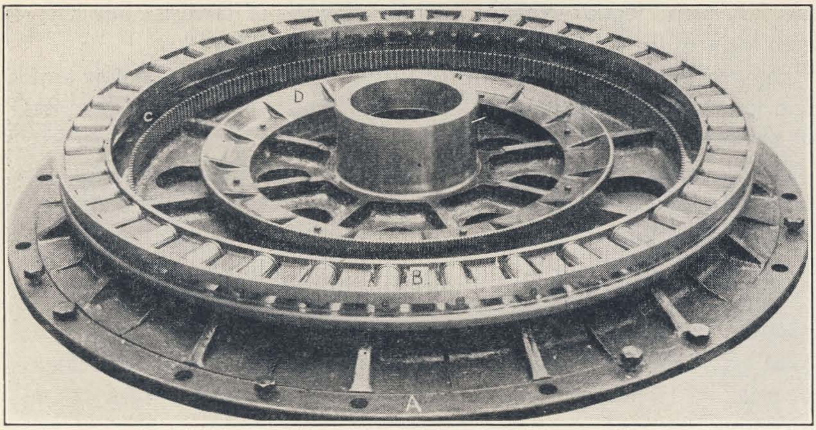


FIG. 142.

nected by suitable gearing to the traversing rack, and the azimuth receiver drive (*D*) connected to the gear (*D*) of the base plate (Fig. 142). Similar dual handwheels, and elevating gear box, are mounted on the opposite side of the pedestal.

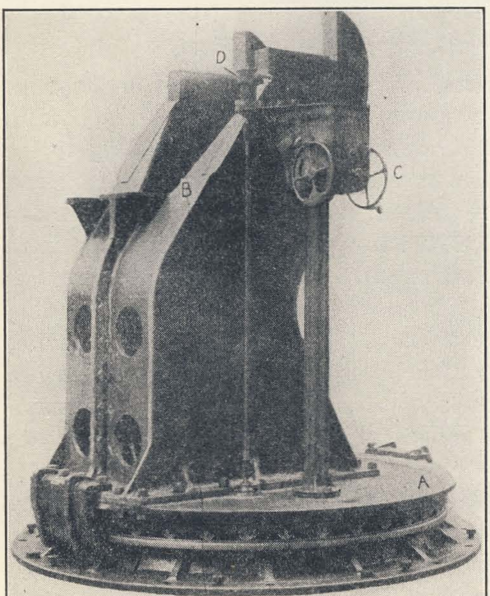


FIG. 143.

The mount is shown in Fig. 144, with the gun at 0° elevation. The cradle supports the gun, and assembles the recoil and recuperator mechanisms, the pneumatic loading rammer mechanism, and the elevating rack. It is supported on its trunnions in antifriction bearings, the distribution of weight being such that the axis of rotation of the tipping parts is close to the breech of the gun. A single hydraulic recoil cylinder is provided, with a dashpot type of counter-recoil buffer at the front end. The recuperator consists of two spring cylinders, each comprising

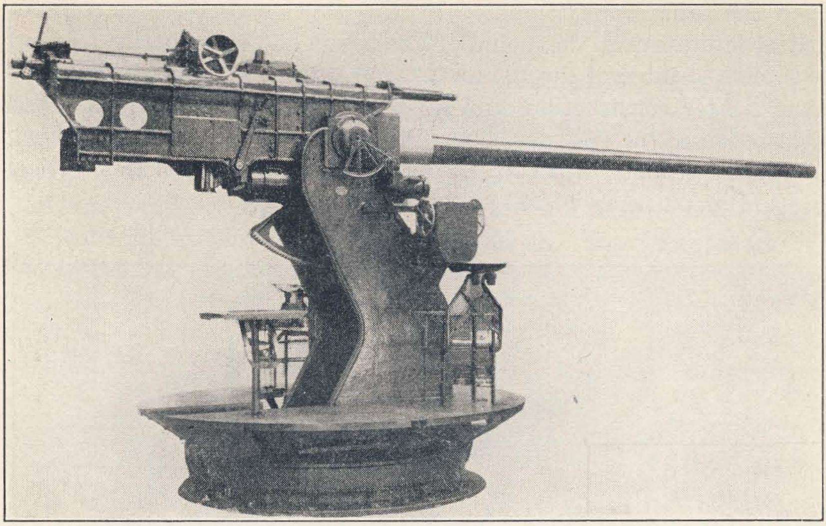


FIG. 144.—105-mm. A. A. Gun Mount, M1.

two concentric columns of helical springs, divided into two longitudinal sections.

The laying of the gun is controlled by an antiaircraft director, which transmits data electrically through an underground cable, leading through a 360° electrical contact unit in the base to azimuth, elevation, and fuze indicators on the mount. The gun is elevated and the mount traversed by the handwheels until the pointers indicating the position in elevation and azimuth match the pointers in the indicators actuated from the director.

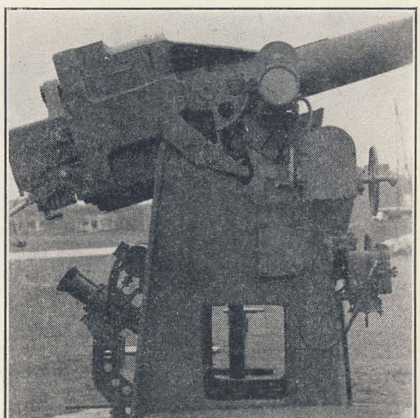


FIG. 145.—3-in. A. A. Gun Mount, M1917MII.

247. The 3-in. Antiaircraft Gun Mounts.—Following the World War a number of 3-in. antiaircraft fixed mounts were installed in the harbor defenses. Figure 145 illustrates a modification of this early type of mount to adapt it for use with the modern automatic fire-control system, in

which the firing data computed by the director are received continuously at indicators on the mount. The design and construction features are similar to those of the 105-mm. A. A. Mount, M1, except that they are of lighter construction, and no power rammer is provided. The construction of the gun was shown in Fig. 55. It fires a 12.7-lb. shell, at a muzzle velocity of 2800 f. s., the maximum horizontal and vertical ranges attained being 14,200 yd. and 9700 yd. respectively.

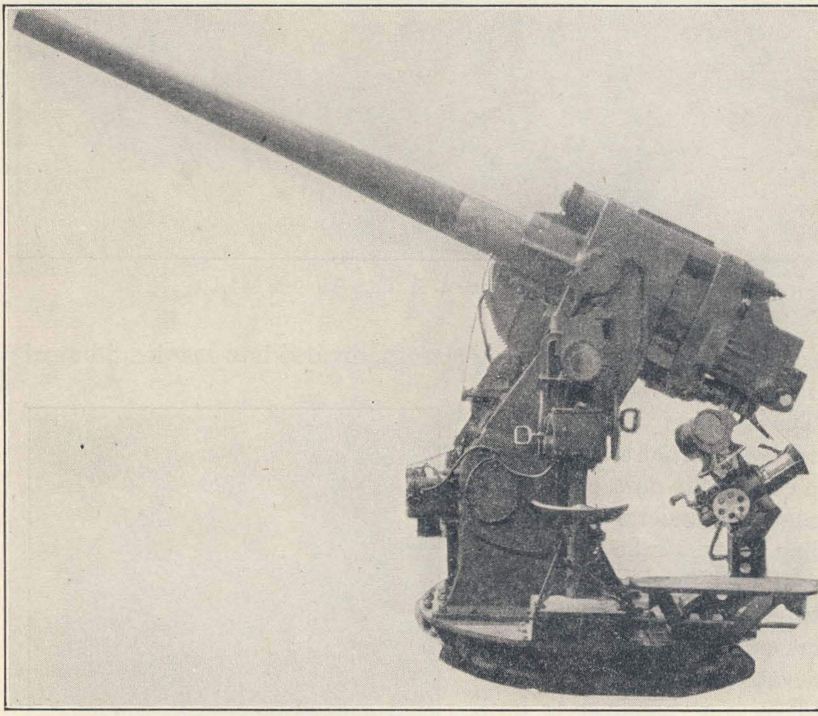


FIG. 146.—3-in. A. A. Gun, M4, on Mount, M3.

A later mount is shown in Fig. 146, very similar to the 105-mm. A. A. Mount, M1, except in size. With the M4 gun the maximum horizontal and vertical ranges are the same as in other 3-in. mounts, 14,200 yd. and 9700 yd., respectively. Only a very small number of these mounts have been constructed. It is probable that future harbor defense requirements for this caliber of antiaircraft weapon will be met by use of mobile mounts.

MOBILE ANTIAIRCRAFT MOUNTS

248. The 3-in. Antiaircraft Gun, M3, on Mount, M2A1.—This is the latest standard mobile antiaircraft gun mount. A battery in firing position is shown in Fig. 147, and one mount in the traveling position in Fig. 148. The gun is of two-piece construction, consisting of a tube and removable or loose liner, with a breech ring screwed to the rear of the tube to support the breech mechanism. The breechblock is a vertical sliding type, semi-automatic in operation, opened automatically just before the end of counter-recoil, and closed automatically as the fixed round of ammunition is inserted by hand. The gun fires a 12.7-lb. high-explosive shell, with a muzzle velocity of 2800 f.s., attaining maxi-

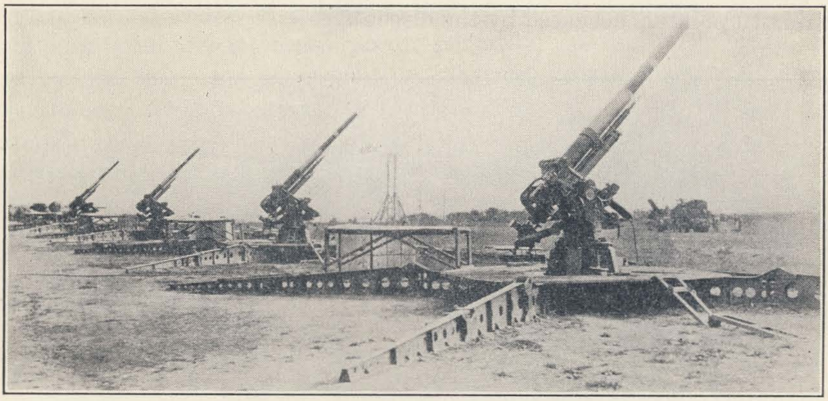


FIG. 147.—3-in. Mobile Mount, Firing Position.

mum horizontal and vertical ranges of 14,200 yd. and 9700 yd., respectively.

The gun is mounted in a cradle which is supported on its trunnions in antifriction bearings on the arms of the pivot yoke. A hydropneumatic recoil system is employed, dependent type, with floating piston, somewhat similar to the Puteaux system described in Chapter VII, but with a hydraulic counter-recoil buffer cylinder in the front end of the recoil cylinder. The tipping parts are trunnioned well in rear of their center of mass, which is made possible by provision of an equilibrator on each side.

The weight of the traversing parts is supported by ball bearings on the top of the pedestal, and by a radial bearing on the lower end of the pivot yoke. In the firing position, the broad under surface of the pedestal rests on the ground; attached to the pedestal by pivot pins are

four outriggers, each of three sections, which afford rigid support to the mount in firing. Outriggers of welded steel construction have replaced those of cast duralumin, giving greater strength for the same weight. The outriggers also support the perforated aluminum working platform around the gun.

Traverse and elevation are accomplished by dual handwheels mounted on gear boxes, which operate through gear trains of conventional type, similar to the mechanism of the 105-mm. Mount, M1. Each gear train contains a self-locking worm and worm wheel to prevent the transmission of firing stresses to the handwheels.

For laying the guns, the *match-the-pointer* system is used, the piece being elevated and traversed until the positions of its pointers in the indicators match the positions of the corresponding elevation and azimuth pointers actuated by the director.

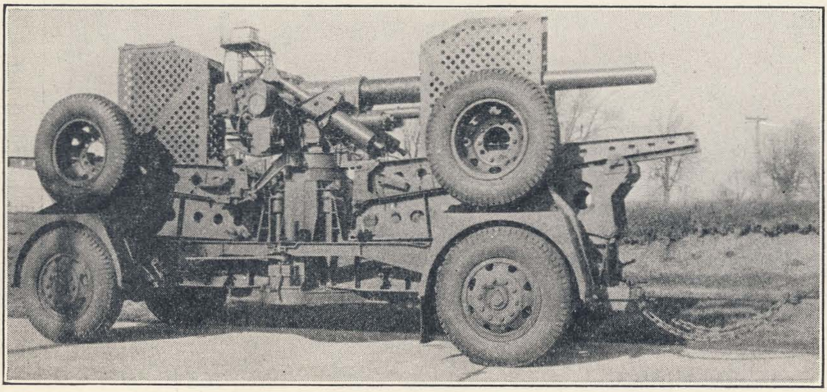


FIG. 148.—3-in. Mobile Mount, Traveling Position.

For travel, the outriggers are folded and locked together, forming the chassis of the mobile mount. The mount is supported and travels on front and rear bogies, both of which are two-wheeled, with pneumatic tires, and with heavy leaf springs for suspension. The total weight of the mount in traveling position is approximately 8 tons. A special drawbar is provided for towing, and the mount is equipped with air brakes operated from the prime mover.

To emplace the mount for firing, the lifting jacks are lowered until all weight is off the bogies, which are then removed. The outriggers are then unfolded and spread, and the jacks are run up, thus lowering the mount until the pedestal rests on the ground. A well-trained gun crew can go into action from the traveling position in from 7 to 10 minutes.

MOBILE ARTILLERY

249. Types.—Mobile artillery comprises various guns, howitzers, and mortars designed to accompany an army in the field, or capable of being transported from place to place as required. The widely varying tactical requirements and conditions of employment can only be met by provision of a considerable number of classes, types, and calibers of weapons, adapted to different methods of transport.

The characteristics provided by any design of artillery weapon are based, primarily, upon tactical requirements. The characteristics include caliber of weapon, maximum range, rate of fire, traverse and elevation permitted by the carriage or mount, weight and mobility, time required to emplace, and weight and capacity of projectile. Certain of the requirements imposed or desired may be conflicting or opposing; for example, increased power normally necessitates increase in weight and may decrease mobility. Likewise, provision of the gun elevation and carriage traverse limits desired may complicate the design unduly. Compromise becomes necessary, and the designs finally evolved and standardized are those which most nearly satisfy the tactical requirements. The characteristics of an adopted design have a definite bearing on their subsequent employment.

The so-called *all-purpose* mounts, designed for several classes of fire ordinarily requiring employment of several types of matériel, have not proved successful or practicable.

Mobility is a relative term. Tactical mobility refers to the characteristic ability of matériel to move readily and quickly from one position to another on the battlefield or across country. Strategic mobility refers to its ability to move great distances in short periods of time, as on roads. The introduction of mechanical traction for artillery transport has increased the strategic mobility of artillery; this, with provision for dividing heavy matériel into several loads, when necessary, has permitted increase of weight limits in certain types, or use of weapons of greater power. Utilization of mechanical traction has also increased the tactical mobility of certain types of weapons.

Based upon weight and caliber, mobile artillery is classified broadly as *light*, *medium*, and *heavy* artillery. Light artillery comprises the 105-mm. howitzer, the 75-mm. gun, the 75-mm. howitzer, and weapons of smaller caliber; it includes those weapons which are able, normally, to keep pace both on the road and across country with the arms they are supporting. Medium artillery comprises the 3-in. antiaircraft gun and the 155-mm. howitzer, weapons of greater weight and less tactical mobility. Heavy artillery comprises the 155-mm. gun, the 8-in.

howitzer, the 240-mm. howitzer, all guns and howitzers of larger caliber, and all railway artillery.

From the standpoint of organic allotment to tactical echelons, artillery is classified as follows:

- Infantry accompanying weapons.
- Division artillery.
- Corps artillery.
- Army artillery.
- G. H. Q. (general headquarters) reserve artillery.

The G. H. Q. reserve artillery includes all artillery not an organic part of divisions, corps, and armies, under the command of the field forces. It includes types and calibers similar to the organic artillery of divisions, corps, and armies, together with heavier calibers and types suitable for special operations. In addition to its organic artillery, an echelon may have attached to it other artillery which has been allotted or re-allotted by the next higher echelon.

The missions of artillery with the divisions, corps, and armies require the use of both guns and howitzers. Generally speaking, each gun has as a companion piece a howitzer of greater caliber, of approximately the same mobility, firing a projectile of approximately twice the weight, but with less muzzle velocity and shorter maximum range. Usually it is not practicable to design a carriage which will permit selective mounting of either the gun or the howitzer, because of the different characteristics of the two weapons. An exception to this, however, is the 155-mm. gun—8-in. howitzer carriage which will be described later.

Mobile artillery is classified according to the means of transport as follows:

- Horse-drawn artillery.
- Horse artillery.
- Pack artillery.
- Truck-drawn artillery.
- Tractor-drawn artillery.
- Railway artillery.

The first three classes include no weapon larger than 75 mm. in caliber; they have high tactical mobility but low strategic mobility. The truck-drawn weapons include the 75-mm. howitzer, 75-mm. gun, 3-in. anti-aircraft gun, the 105-mm. howitzer, and larger guns and howitzers when equipped specifically for high-speed towing.

The table shows the principal characteristics of the standard types of mobile artillery matériel in the United States service. Certain of these

weapons are of new and improved design, others are of World-War types but modified and improved in certain respects, and others represent unmodified war matériel. Until replaced by newer designs, the older types remain standard; although deficient in some respects as compared with more modern types, they constitute effective artillery. Certain weapons of each of these classes will be described to illustrate designs and design trends.

CHARACTERISTICS OF MOBILE ARTILLERY

(Railway Artillery Not Included)

Type and Caliber	Carriage Model	Weight of Gun and Carriage in Firing Position	Maximum Traverse	Maximum Elevation	Projectile, Lb.	Muzzle Velocity f/s	Maximum Chamber Pressure lb./sq. in.	Maximum Range, Yd.
Division:								
75-mm. Gun (French)..	1897M1	2,660	6°	19°	13.5	1955	36,000	9,200
75-mm. Gun (French)..	(b) 1897A4	2,890	6°	19°	13.5	1955	36,000	9,200
75-mm. Gun (French)..	M2	3,500	90°	45°	13.5	1955	36,000	12,780
75-mm. Howitzer......	M3A1	2,060	45°	45°	14.19	1270	26,000	9,490
105-mm. Howitzer......	M1	3,700	45°	65°	33.0	1550	28,000	12,150
Corps:								
155-mm. Howitzer......	1918	8,350	6°	42°	95.0	1480	30,000	12,400
155-mm. Howitzer......	(b) 1918A1	8,960	6°	42°	95.0	1480	30,000	12,400
Army:								
155-mm. Gun (G. P. F.).	1918	25,960	60°	35°	95.0	2410	31,500	17,400
155-mm. Gun (G. P. F.).	(b) 1918A1	26,000	60°	35°	95.0	2410	31,500	17,400
8-in. Howitzer........	(d) MK. VII	20,050	8°	45°	200	1525	32,000	12,360
240-mm. Howitzer......	1918	41,300	20°	60°	345	1700	33,000	16,390
Infantry:								
37-mm. Gun..........	1916	(a) 180	42°	21°	1.25	1276	18,500	4,900
3-in. Trench Mortar..	MK. IA2	110	17°	75°	7.2	564	4,000	2,565
81-mm. Mortar........	M1	126	8.5°	80°	7.2	637	6,000	3,280
Antiaircraft:								
3-in. Gun............	M2A1	12,000	360°	80°	12.7	2800	36,000	(c)9,700
Pack:								
75-mm. Pack Howitzer.	M1	1,300	6°	45°	14.19	1270	26,000	9,490

(a) Tripod mount.

(b) World-War type modified for high speed.

(c) Vertical range.

(d) World-War type, now limited standard. See Section 258 for illustration of modern carriage which will mount either the 155-mm. gun or the new 8-in. howitzer which has a maximum range of 18,700 yd.

250. The 75-mm. Gun and Carriage, Model of 1897 (French).—The 75-mm. Field Gun, Model of 1897 (French), has been the standard

division weapon since the World War. The gun and carriage of French design, and of French or American manufacture, are illustrated in Fig. 149.

Both the gun and the carriage have been modified, and the modified gun has been mounted on a carriage of new design, as will be described

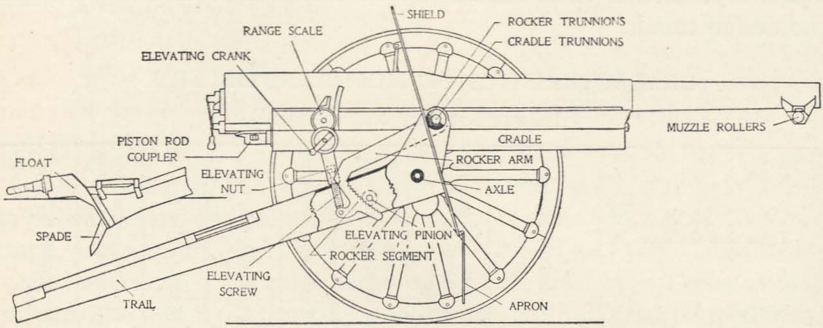


Fig. 149.—75-mm. Field Gun and Carriage, Model of 1897 (French), Right Side.

in subsequent sections. In this section the matériel described is that originally standardized for use in the United States service.

The Gun.—The gun is of built-up type, 34.5 calibers in length. Its construction is illustrated in Fig. 150. A breech hoop shrunk over the

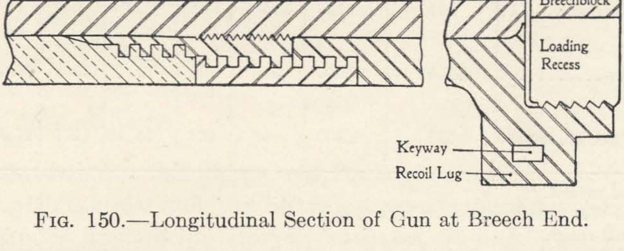


Fig. 150.—Longitudinal Section of Gun at Breech End.

rear of the tube supports the breechblock. The inner locking hoop is screwed on the tube and abuts against the breech hoop. The outer locking hoop serves to lock together the inner locking hoop and the breech hoop. A bronze jacket over the middle portion of the tube is

screwed on the inner locking hoop. The assembly is thus securely locked together.

The recoil lug which is a part of the breech hoop connects the gun to the recoil mechanism. Bronze slides and three sets of rollers attached to the gun (Fig. 156) support the gun as it slides through the cradle in recoil.

The carriage permits maximum traverse of 6°, or 3° on either side of the normal, and firing elevations up to 19° only. At this elevation the maximum range obtainable depends upon the projectile used, being 9200 yd. for the standard 13.5-lb. H. E. Shell. By lowering the rear end of the trail to increase the gun elevation, the range may be increased to a maximum of 12,780 yd. at 44° elevation.

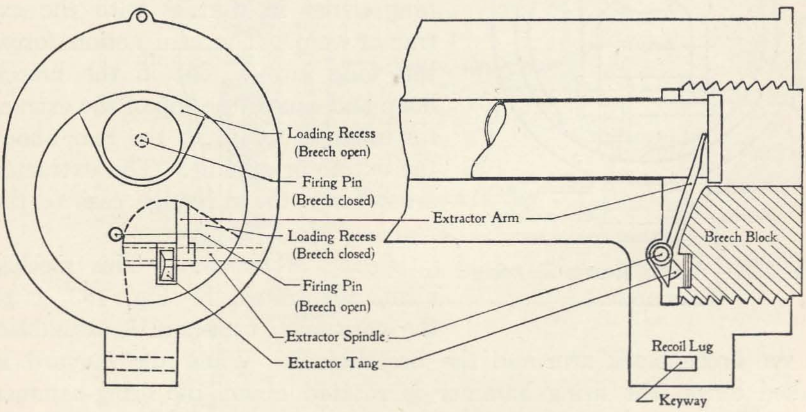


FIG. 151.—Details of the Breech Mechanism.

Breech Mechanism.—The breechblock is shown in Fig. 151. It is of the eccentric screw type, cylindrical in shape, and threaded on its exterior to screw into the breech recess. It has a large diameter compared with the caliber of the gun because the axis of rotation of the breechblock is below the axis of the bore. The block remains in the breech recess during the action of both loading and firing, and the opening and closing of the breech are accomplished by rotating the breechblock about its axis. A large hole, or loading recess, is cut through the exterior of the block on one side, making a U-shaped passage for the insertion of ammunition into the chamber of the gun. A small hole, the firing-pin hole, is bored through the breechblock to receive the firing pin. For the loading or "open" position, rotation of the block locates the loading hole opposite the chamber; for the firing or "closed" position, the rotation locates the firing-pin hole opposite the axis of the bore.

The gun cannot be fired except when the breechblock is fully closed, which is the only position in which the firing pin is directly in line with the axis of the bore.

Extractor.—When the breech is opened the cartridge case is automatically extracted and ejected by means of the extractor, shown in Figs. 151 and 152. A circular groove, whose depth is equal to the projection of the heel of the extractor tang, is made in the front face of the breechblock. At the end of this groove is an extractor cam. Just prior to completion of the movement of opening the breech, the extractor tang comes in contact with the extractor cam. The cam action forces the tang into a slot in the breech hoop and causes the top of the extractor arms to rotate to the rear about the extractor spindle. The extractor arms carry the cartridge case to the rear and eject it.

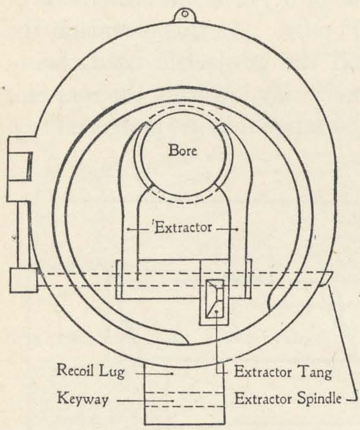


FIG. 152.—Breech Recess Showing Extractor.

Firing Mechanism.—This mechanism, illustrated in Fig. 153, is of the percussion type and is assembled in the breechblock arm and the breechblock. When the lanyard is pulled down, the firing hammer is rotated about the firing-hammer pin. The gear teeth of the firing hammer engage with the firing rack. The rack moves in the direction indicated by the arrow, *A*, thus compressing the firing-rack spring. When the lanyard is released, the hammer is thrown against the firing pin by the compressed spring. Thus the firing pin is driven forward to fire the primer.

The Carriage.—(Fig. 149.) The principal parts are the trail, wheels and axle, rocker, cradle, elevating and traversing mechanisms, recoil system, shields, and wheel brakes.

Trail.—The primary function of the trail is to stabilize the carriage during firing. It consists essentially of an axle housing, a spade and float, and two long flasks or side plates connected and braced by a top plate and by cross beams known as transoms. All parts are rigidly bolted and riveted together. The side plates are extended above the axle to form the support and bearings for the rocker trunnions.

Axle.—The axle is a hollow steel forging machined to prescribed dimensions. The central part of the left half is threaded on the exterior and engages with the traversing nut, as shown in Fig. 154.

Cradle.—The cradle, shown in cross section in Fig. 155, supports the gun at all times, guides it during recoil and counter-recoil, and con-

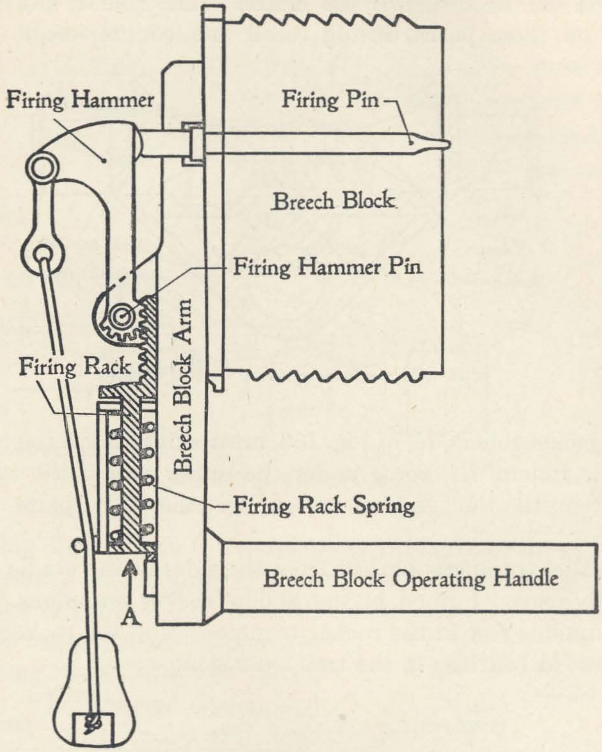


FIG. 153.—Details of the Firing Mechanism.

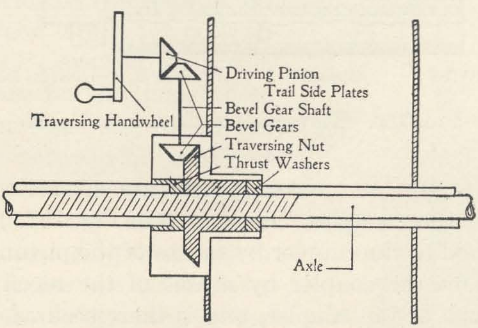


FIG. 154.—Schematic Drawing of Traversing Mechansim.

tains the recoil system, which is of the Puteaux type, described in Chapter VII.

The cradle body is a steel forging, its ends and lower diagonal sides being covered by steel plates. Upper and lower roller paths are formed on the inside of the cradle. The rollers, pivoted on the gun, roll on these paths during recoil and counter-recoil. In recoil,

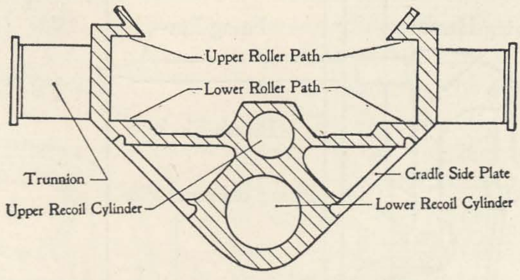


Fig. 155.—Cross Section of the Cradle.

when the jacket rollers, R_3 of Fig. 156, are about to leave the roller paths, the muzzle rollers, R_1, come under the upper paths; the tube is then supported until the end of recoil by the two pairs of rollers, R_2 and R_1.

The cradle trunnions project from the sides of the cradle and rest in trunnion bearings, formed in the hollow rocker trunnions. Thus the cradle trunnions rest in the rocker trunnions, and the rocker trunnions, in turn, rest in bearings in the trail extension.

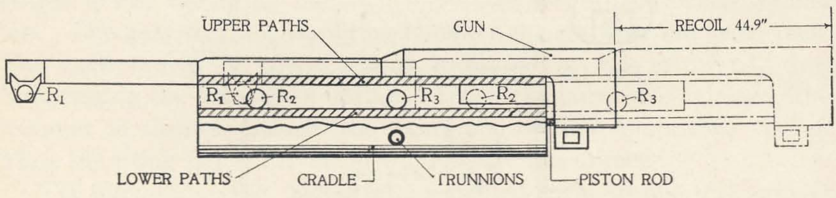


Fig. 156.—Movement of the Gun in Recoil.

Coupler.—The gun and recoil system are connected by means of a piece known as the "coupler," illustrated in Fig. 157. The recoil piston rod is attached to the coupler by means of the piston rod nut. The gun is attached to the coupler by means of the recoil lug which fits between the wings of the coupler, and is there secured by the coupler key. During recoil the gun, coupler, and piston rod move to the rear as a unit.

Safety Bolt.—The safety bolt is a device, shown in Fig. 158, which prevents firing the gun except when it is coupled to the piston rod.

A cam groove is cut in the rear face of the coupler key, and a lug on the safety bolt engages in this groove. Only when the breech is open can the coupler key be removed. When the coupler key is removed, the

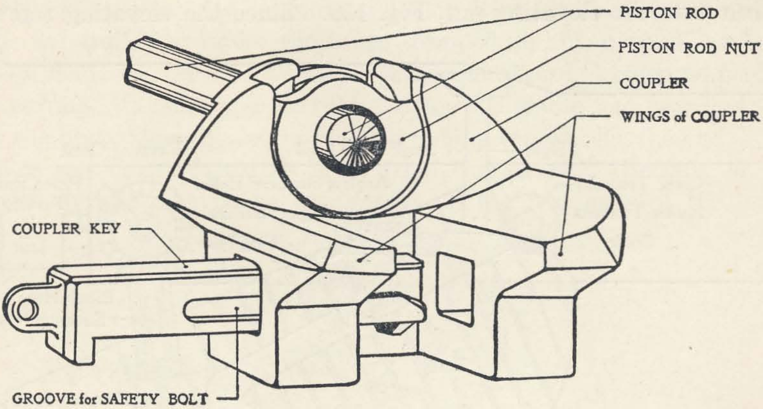


FIG. 157.—The Coupler.

safety bolt lug operating in the coupler-key cam groove raises the safety bolt. The safety bolt then protrudes into the breech recess, engages in a hole in the breechblock, and locks the block in the open position.

Elevating Mechanism — Rocker. — The elevating mechanism is shown in Fig. 159. The carriage is equipped with the *independent line of sight*; that is, the elevating system provides separate and independent mechanisms for laying off the angle of site for position and the angle of elevation for range. To provide means for obtaining these two elevation settings, the rocker has been interposed between the trail and the cradle. It is that part of the carriage on which the cradle rests. It pivots in its trunnion bearings in the trail. The rocker is rotated about the rocker trunnions by turning the angle-of-site elevating handwheel, not shown in the figure, which actuates the elevating pinion, H, geared to the rocker segment. As the rocker is connected to the cradle by the elevating nut and elevating screw,

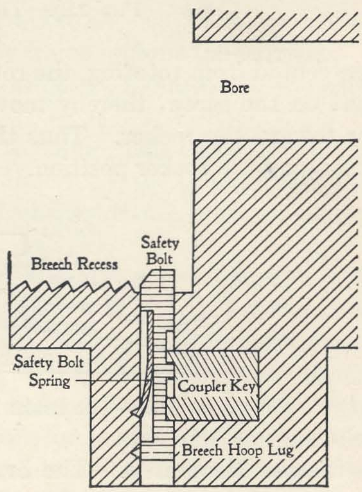


FIG. 158.—The Safety Bolt.

movement of the rocker segment up or down moves the gun in the same direction. The sight is rigidly attached to the rocker.

To elevate or depress the gun without changing the position of the rocker or the line of site, the elevating crank is turned and the bevel gears rotate the elevating nut, Fig. 159. Since the elevating screw is

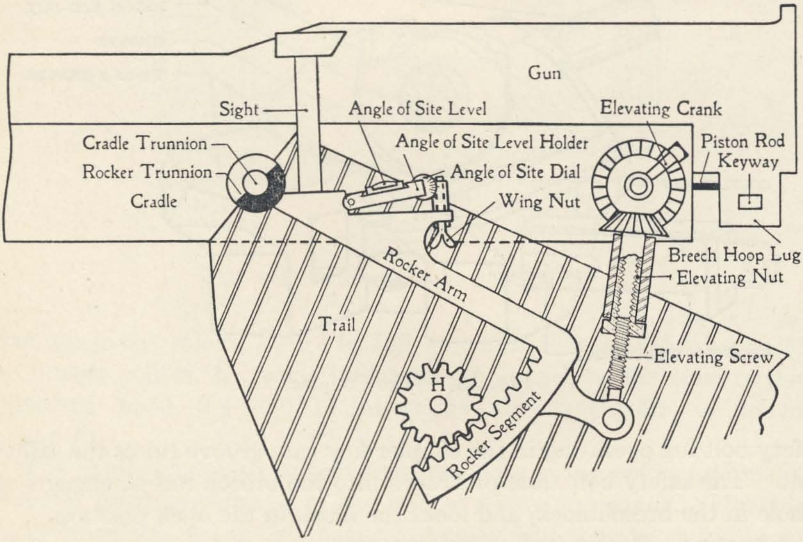


FIG. 159.—The Elevating Mechanism.

prevented from rotating, the rotation of the elevating nut advances the nut on the screw, thereby moving the cradle and the gun away from or toward the rocker. Thus the gun is elevated or depressed without changing the rocker position.

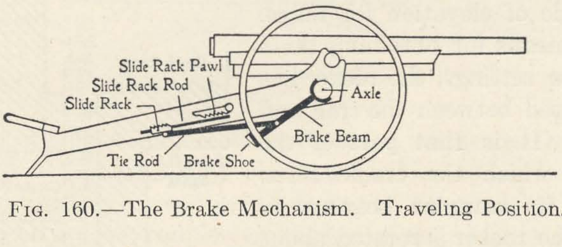


FIG. 160.—The Brake Mechanism. Traveling Position.

Brake Mechanism.—The brake is designed to serve both as a road brake and as a firing brake. The principal parts are: tie rods, brake beams, braces, and compensating bar, which make up the frame of the brake; and brake-beam crank, brake shoes, slide rack, and slide-rack pawl.

When traveling, the frame is latched up and the brake shoes are in position behind the wheels. They are applied against the tires by the operation of the brake crank.

To prevent lateral displacement of the carriage and to reduce the vibration of the parts to a minimum during firing, the frame is unlatched from the trail, the brake shoes are dropped to the ground, and the wheels made to rest on the shoes. This operation is known as placing the carriage *in abatage* (Fig. 161). After the frame has been lowered and the brake shoes placed in position behind the wheels, the end of the trail is raised approximately 3 ft. from the ground. Because of the weight of the brake frame, the spades on the rear ends of the brake

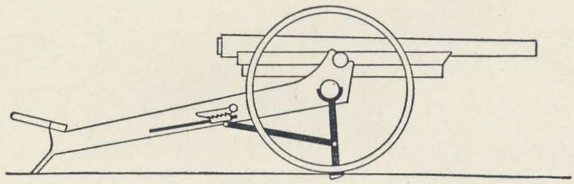


FIG. 161.—The Brake Mechanism. In Abatage.

beams remain on the ground. The front ends of the brake beams pivot about the axle, the slide rack slides forward along the slide-rack rod and engages with the slide-rack pawl. The trail is then lowered to the ground and the wheels rolled back on the brake shoes. In this position, the brake shoes act as a platform and the frame stiffens the carriage.

Wheels.—Wooden wheels, steel-tired, are used, mounted on the axle without use of any antifriction bearings.

251.—The 75-mm. Gun Carriage, M1897A4.—This carriage mounts the 75-mm. Gun, M1897 (French), just described, the original carriage having been modified to adapt it for high-speed transport, as shown in Fig. 162.

The following is a brief description of the high-speed adapter. On each end of the unaltered carriage axle is mounted an axle bracket. A spindle inserted at the lower end of each bracket supports on roller bearings the hub of a commercial disc-type wheel, to which the brake drum is attached. Commercial heavy-duty balloon tires are used, with puncture-sealing inner tubes. The brakes, of commercial automobile type, are actuated by brake levers mounted on the brake shaft at the left side of the carriage.

A compensator shaft slides freely in its bearings in supporting brackets attached to the trail at either side. A radius rod connects each end of the compensator shaft with the corresponding axle bracket.

A supporting *wishbone*, of angle iron bent into an irregular U-shaped piece, is attached at each end to the axle collar. A ball stud at the center of the compensator shaft fits into a ball socket at the rear of the wishbone. The relation between wishbone, compensator shaft, and radius rods affords requisite support and permits the necessary movement as the carriage is traversed.

No other parts or characteristics of the carriage are affected by the modification. The maximum traverse and elevation of the original

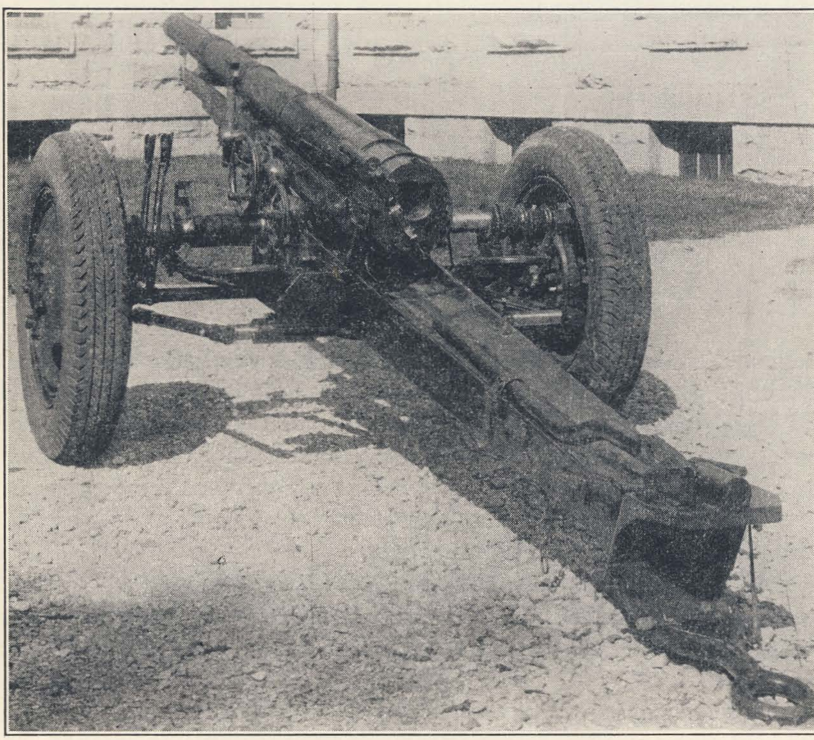


FIG. 162.—75-mm. Gun Carriage, M1897A4.

carriage are not increased. The gun is fired with the pneumatic tires resting on the ground. The carriage is stable at all firing elevations. It can be towed behind a truck at speeds of 45 miles per hour without damage. A large number of carriages in service have been modified.

252. The 37-mm. Subcaliber Mount, M2.—(Fig. 163.) This is the subcaliber equipment for the 75-mm. Gun, M1897 (French). It consists of a front and a rear support, assembled to the gun tube, forming a

rigid mount for the 37-mm. gun and its recoil mechanism. This illustrates the modern practice of mounting the subcaliber equipment on the outside of the major weapon. Similar equipment is provided for installation on other types of field artillery weapons.

253. The 75-mm. Gun Carriage, M2.—This carriage mounts the 75-mm. Gun, M1897A1, a modification of the M1897 French type. The standard French Puteaux recoil mechanism is used, modified in certain minor details.

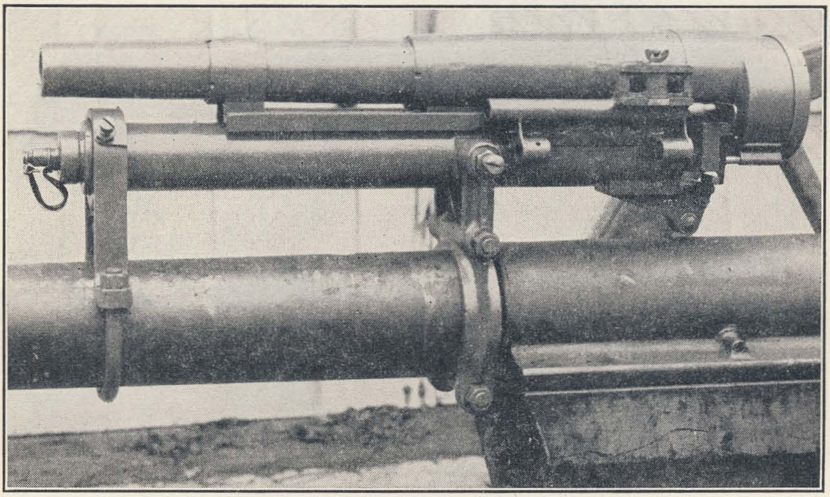


FIG. 163.—37-mm. Subcaliber Mount, M2.

The carriage, illustrated in Figs. 164–166, incl., is of completely new design. It is of the split-trail type, permitting gun elevations between $-10°$ and $+45°$, and traverse of 90°. The carriage permits attainment of the full range potentialities of the gun, 12,780 yd. with the 13.5-lb. H. E. Shell. The axis about which the tipping parts move in elevation is considerably in rear of their center of mass, close to the breech of the gun, the muzzle preponderance being balanced by two spring-type equilibrators.

The carriage is designed for high-speed travel. It is equipped with disc-type wheels mounted on roller bearings, with heavy-duty pneumatic tires and puncture-sealing inner tubes. Brake drums are mounted on the wheel hubs; the brakes are of commercial automobile type, actuated by hand levers at the left side of the carriage.

The two trails are hinged to the ends of the axle, and are adjustable for either a 45° or 90° spread; they are locked together for traveling.

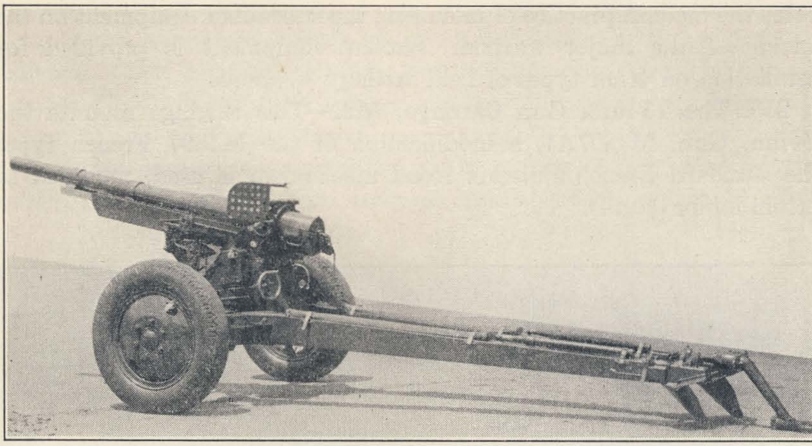


FIG. 164.—75-mm. Gun Carriage, M2, with trails closed.

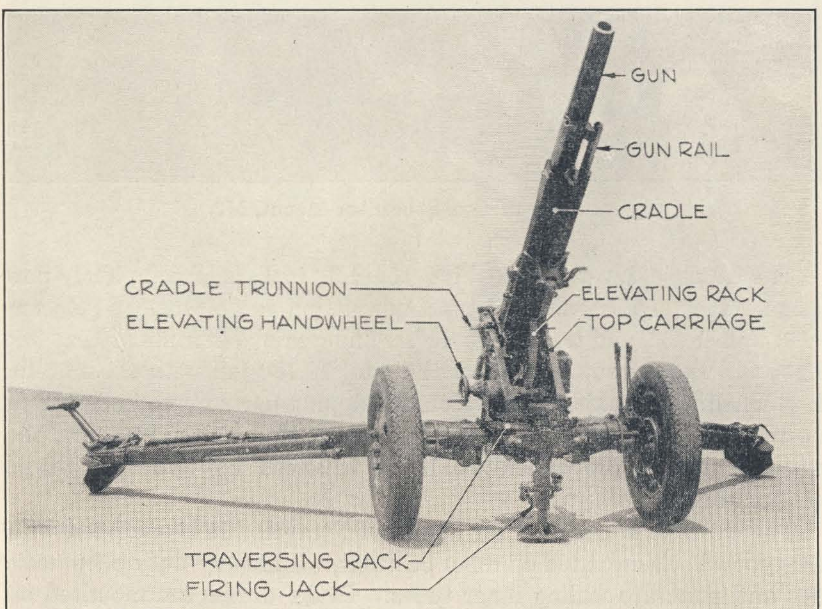


FIG. 165.—75-mm. Gun Carriage, M2, firing position.

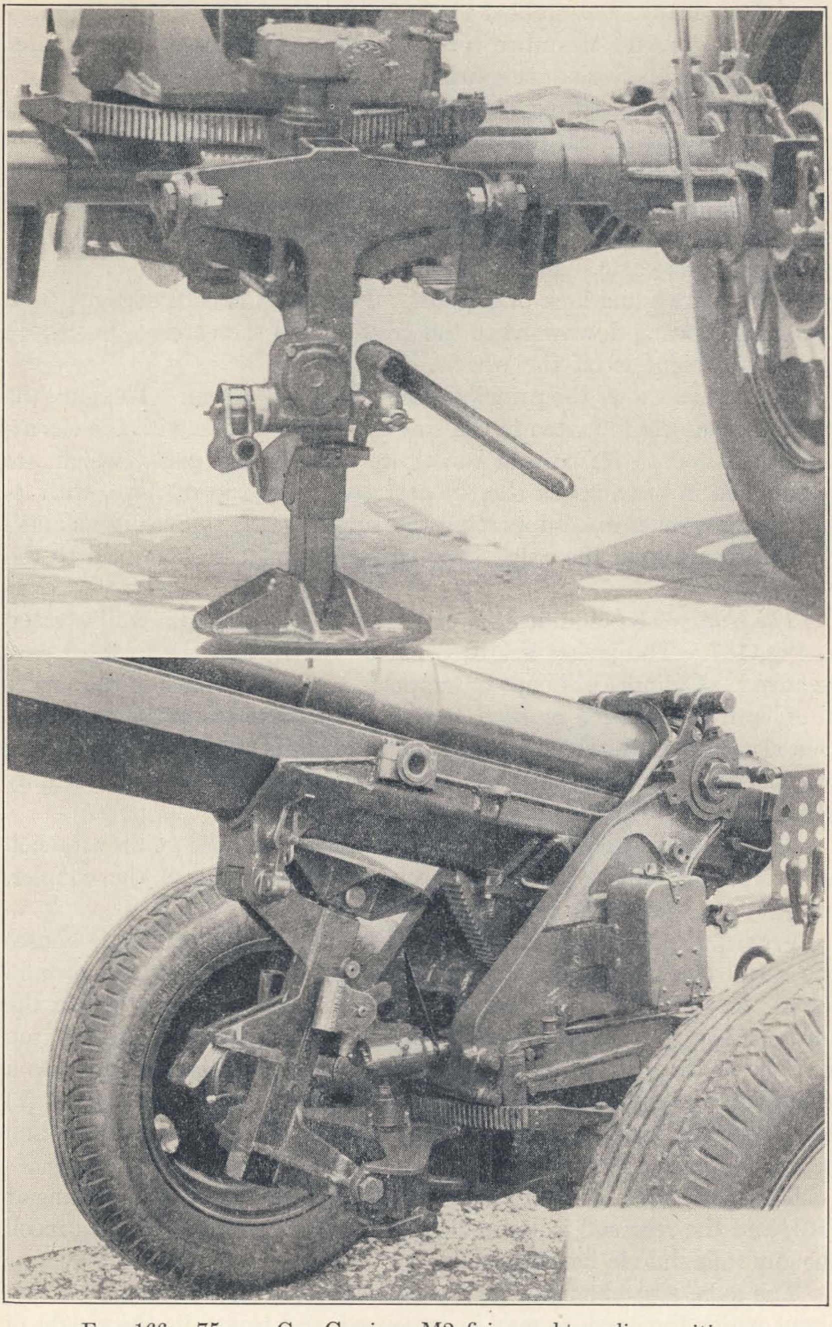


FIG. 166.—75-mm. Gun Carriage, M2, firing and traveling positions.

The offset drawbar assembled to the rear end of the right trail insures the necessary road clearance for the spades (Fig. 164). It is rotated upward out of the way during firing. (Fig. 165).

The gun may be fired from the wheels (Fig. 164), with the trails either opened or closed, provided that in the latter case the gun is not elevated so high that the recoiling parts will hit the trails; or, the gun may be supported on a firing jack with the wheels off the ground and with the trails spread. (Figs. 165 and upper 166). The jack assembly is hinged to the axle. In travel position, it is locked to the cradle and serves as a traveling lock or support. For firing, it is disengaged from the cradle, swung downward to the ground, and the carriage jacked-up until the weight is off the wheels.

Figure 166 shows the principal features of the design. The gun, the recoil mechanism mounted in the cradle, and the cradle with the elevating arc bolted to its bottom constitute the tipping parts, which are trunnioned in bearings on the top carriage. The top carriage, with its traversing mechanism, supporting the tipping parts, moves in azimuth about a bearing on the axle. The traversing rack is assembled to the axle.

The Gun.—The modification of the M1897 French gun is illustrated in Fig. 167. The jacket has been cut off at (*E*) and the forward part removed. Cylindrical hoops or supports have been fitted to the jacket at *A*, and to the tube at *B*, *C*, and *D*. To these are attached rails *F* (see also Fig. 165), which replace the rollers and guide the gun during recoil. The section through *C-C* shows the construction and assembly of the hoops, rails, and bearing strip.

The breech mechanism has not been altered, and the gun is attached to the piston rod of the recoil mechanism by means of the coupler, coupler key, and safety bolt previously described.

Cradle, Top Carriage, and Axle.—(Fig. 167). The cradle (1) houses the recoil mechanism and supports the gun in the firing position and during recoil. The cradle trunnions (3) rotate on bearings (4) in the top carriage (2). The elevating handwheel is mounted on the top carriage at (5); its motion is transmitted through suitable gearing to a pinion on the shaft at (6), which meshes with the elevating arc (7) bolted to the cradle. Stops (8) on the arc limit the elevation and depression of the tipping parts.

The recoil mechanism (9) is assembled in the cradle by trunnioning at (10), and the rear end is secured to the cradle by studs. During recoil the gun rails slide in bearings (11).

The axle, assembled to the top carriage at (12), provides a bearing about which the carriage may be traversed, and transmits the weight of

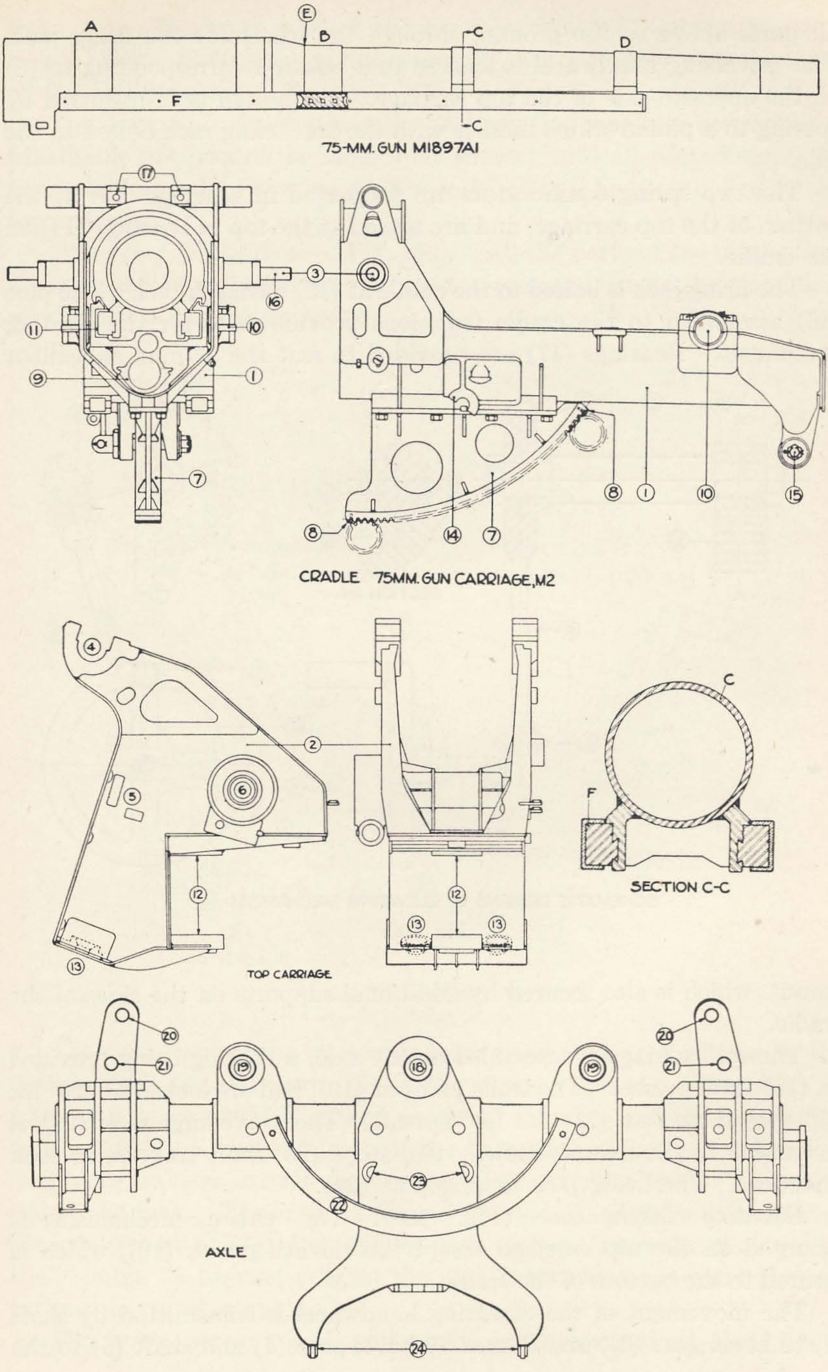
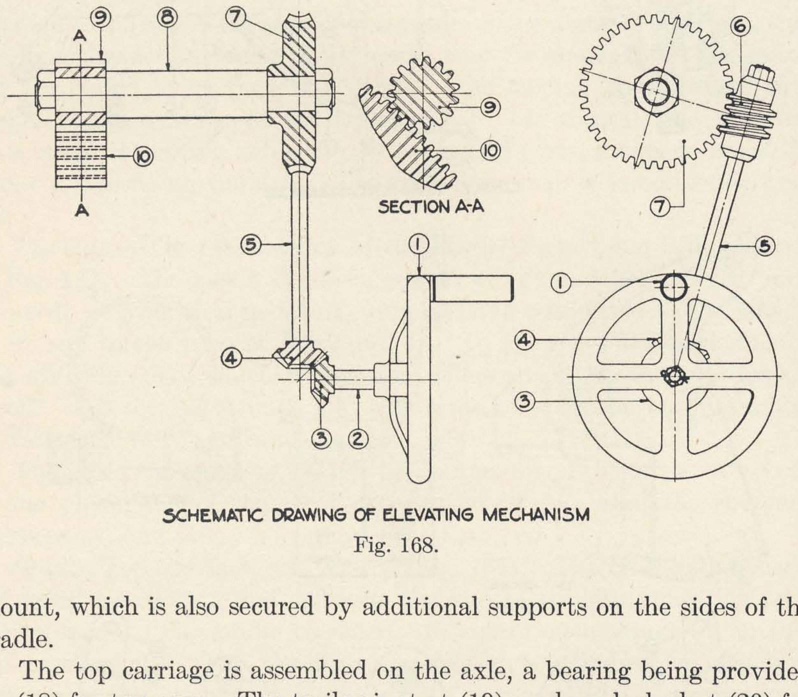


FIG. 167.—75-mm. Gun, M1897A1, and 75-mm. Gun Carriage, M2.

all parts above to the ground, through the wheels or the firing jack. The traversing handwheel is located in a position corresponding to (5) on the opposite side of the top carriage. Its motion is transmitted by gearing to a pinion which meshes with the traversing rack bolted to the axle.

The two spring equilibrators are supported in bearings (13) at the bottom of the top carriage, and are seated at the top in bearings (14) on the cradle.

The firing jack is bolted to the cradle at (15) during travel. The pins (16) assembled to the cradle trunnions provide seats for the sighting equipment. Bearings (17) are provided to seat the 37-mm. subcaliber



SCHEMATIC DRAWING OF ELEVATING MECHANISM

Fig. 168.

mount, which is also secured by additional supports on the sides of the cradle.

The top carriage is assembled on the axle, a bearing being provided on (18) for traverse. The trails pivot at (19), and are locked at (20) for 45° spread and at (21) for 90° spread. The traversing rack (22) is assembled to the axle as shown; two stops (23) limit traverse in each direction. The firing jack is hinged at (24).

Elevating Mechanism.—(Fig. 168). The entire mechanism is mounted on the top carriage except the elevating rack (10), which is secured to the bottom of the cradle.

The movement of the elevating handwheel is transmitted by shaft (2) to bevel gear (3), and thence by bevel gear (4) and shaft (5) to the

worm (6). The worm meshes with the worm wheel (7) on the shaft (8), on the other end of which is the pinion (9), which meshes with the teeth of the elevating arc (10).

The drawing is schematic only. All rotating members are mounted in suitable antifriction bearings (not shown), and all parts except the handwheel and the elevating arc are enclosed in a housing bolted to the top carriage.

Traversing Mechanism.—(Fig. 169). All the parts of the mechanism are mounted on and traverse with the top carriage, except the traversing rack which is secured to the axle.

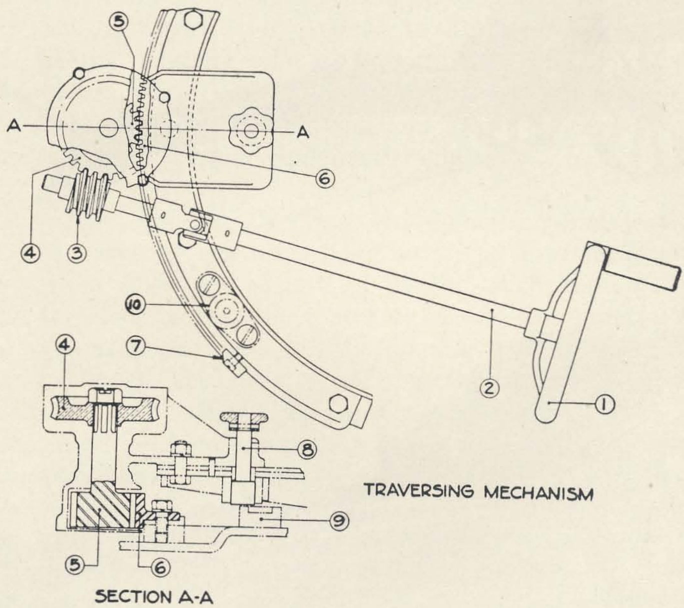


FIG. 169.

The movement of the traversing handwheel (1) is transmitted by the flexible shaft (2) and worm (3) to the worm wheel (4). The shaft to which the worm wheel is splined carries at its other end the pinion (5), which is meshed with the teeth of the traversing rack (6). Control of maximum traverse in each direction is effected by the stops (7) at each end of the rack. The spring-actuated plunger (8) engages stops (9) on the axle (shown at (23), Fig. 167) to limit traverse when the trail spread is 45° only. A bracket (10) on the rack is provided to secure the top carriage in travel position.

The worm, worm wheel, and pinion are supported on antifriction

bearings, and the assembly is enclosed in a housing. The handwheel shaft is supported in a bracket attached to the top carriage.

254. The 75-mm. Howitzer Matériel.—The 75-mm. pack howitzer is mounted on the two types of carriages shown in Fig. 170, the 75-mm.

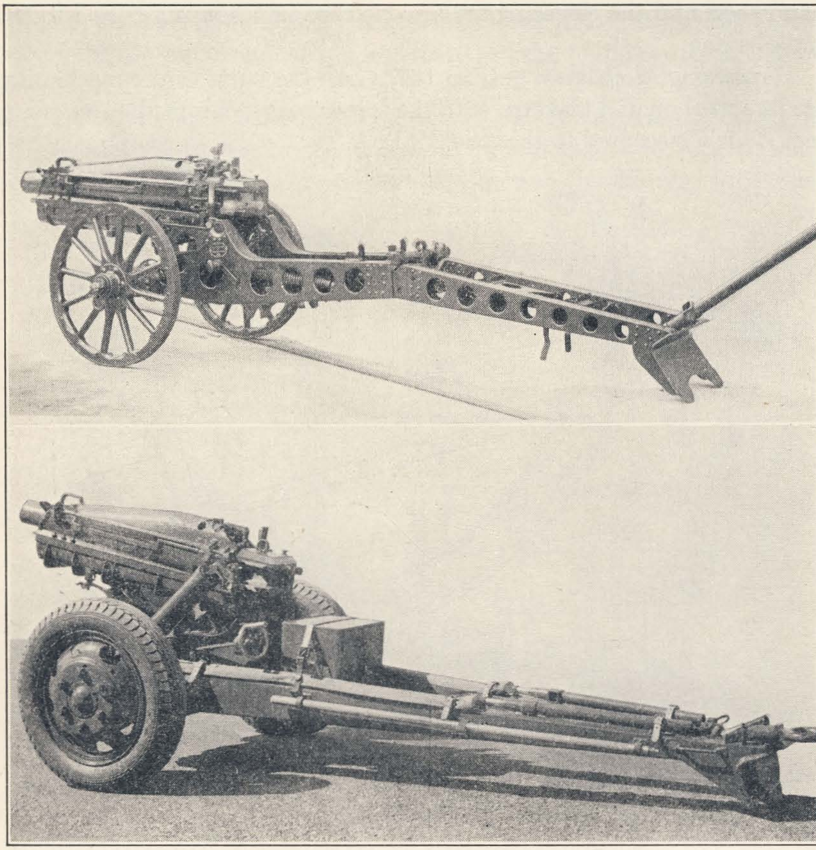


Fig. 170.

75-mm. Pack Howitzer on 75-mm. Pack How. Carr., M1. (*above*)
75-mm. Pack Howitzer on 75-mm. How. Carr., M3A1. (*below*)

Pack Howitzer Carriage, M1, for pack transport, and the 75-mm. Howitzer Carriage, M3A1, designed for high-speed travel. The howitzer has a maximum elevation of 45°, muzzle velocity of 1270 f. s., and a maximum range of 9490 yd. with the 14.2-lb. H. E. Shell, when mounted on either carriage.

The 75-mm. Pack Howitzer Carriage, M1.—The howitzer and its

breech mechanism, the top and bottom sleigh, the cradle, and the recoil mechanism are essentially the same on both carriages. They will be discussed later.

The pack howitzer carriage permits traverse of 6° only, 3° on either side of the normal; the system is one of axle traverse, the left end of the axle being threaded and engaging a traversing nut, the operation being on the same principle as that illustrated in Fig. 154.

The tipping parts are trunnioned close to the breech, the top sleigh being weighted at the rear with lead as a counterweight, and the remaining unbalanced weight being compensated by use of spring equilibrators, set within the front trail, and exerting a pushing force forward.

For pack transport, the matériel is divided into separate pack loads as follows: howitzer tube (excluding breech mechanism); breech mechanism and wheels; cradle and top sleigh; recoil mechanism and bottom sleigh; front trail; rear trail and axle. Other loads include ammunition, fire control equipment, and other accessory equipment.

The 75-mm. Howitzer Carriage, M3.—This matériel is shown in Fig. 171, in traveling and firing positions. The howitzer is supported on the bottom sleigh, and covered by the top sleigh; the bottom sleigh contains the recoil mechanism, consisting of a hydraulic recoil cylinder and a pneumatic recuperator with floating piston. The howitzer, sleighs, and recoil mechanism recoil together, sliding on the cradle; the piston rod is stationary. Two spring-type equilibrators (1) support the unbalanced weight of the tipping parts.

The carriages are equipped with pneumatic-tired wheels, mounted on antifriction bearings for high-speed towing. Standard automobile brakes are provided for each wheel, controlled by separate individual brake levers. The traveling lock is shown at (2), attached to the latch (3) of the cradle.

In going from the traveling position to the firing position, the trails are spread, the traveling lock (2) and the firing base (4) released and swung downward, and the wheel latches (6) released. The spring carriers, on which the wheels are mounted by means of spindles, may now be rotated upward on their bearings in the bottom carriage by means of the handspikes (7). The mount is now supported on the firing base and trail spades. In traveling, the mounting of the wheels in the spring carriers is designed to absorb road shocks. In the later M3A1 carriage, the traveling lock (2) and firing base (4) have been replaced by a single member, as will be illustrated in Fig. 172, and the springs have been eliminated from the carrier.

The traversing handwheel is shown at (8) and the elevating hand-

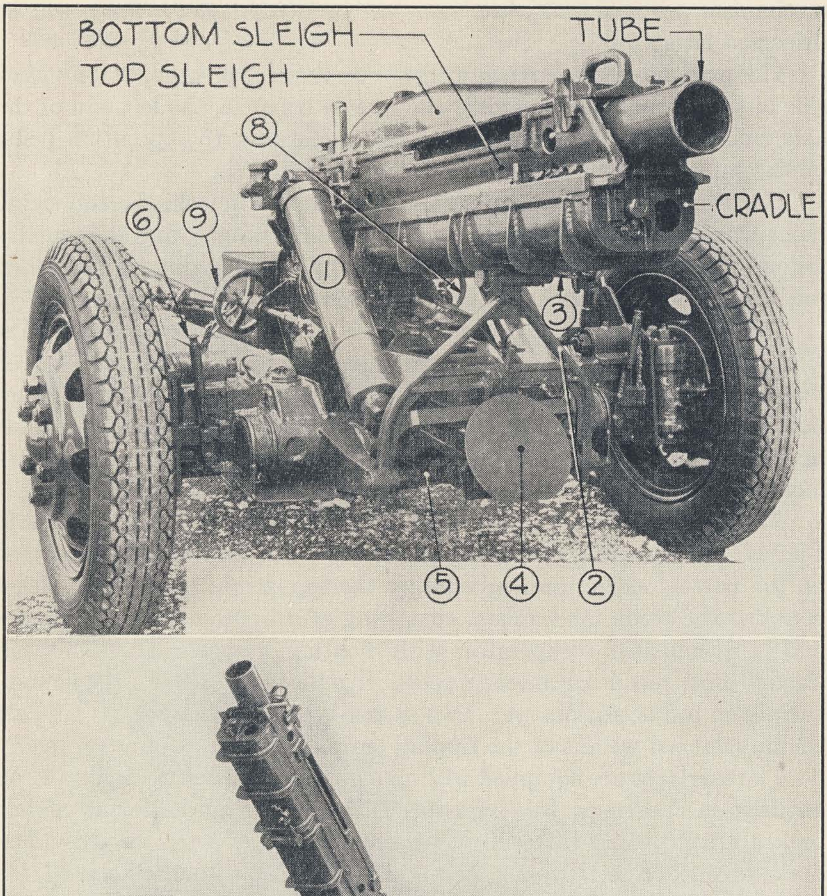


FIG. 171.—75-mm. Howitzer Carriage, M3.

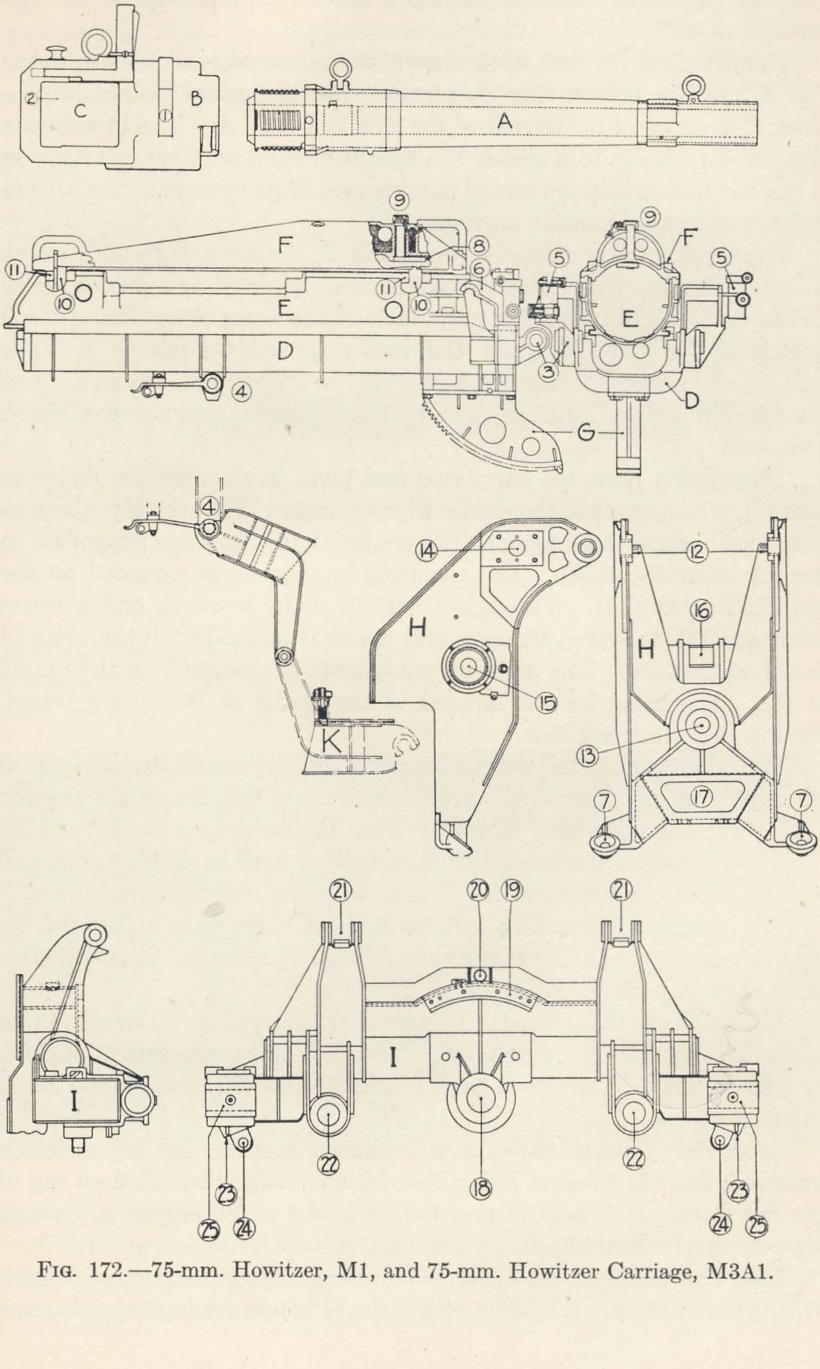


FIG. 172.—75-mm. Howitzer, M1, and 75-mm. Howitzer Carriage, M3A1.

wheel at (9). The carriage permits a maximum elevation of 45° and traverse of 45°.

The principal features of the howitzer and carriage are illustrated in Fig. 172. The breech ring *B*, carrying the horizontal sliding breechblock *C*, is screwed to the rear of the howitzer tube *A*. The breech ring is made detachable to decrease the weight of the pack load. Two keys (1) on the breech ring are seated in corresponding keyways in the bottom sleigh, preventing relative movement.

The tipping parts comprise the cradle *D*, the elevating arc *G*, which is bolted to it, and the members which are supported and slide in recoil on the cradle. The recoiling parts include the lower sleigh *E* and recoil cylinders, the howitzer, and the lead-weighted top sleigh *F*. The cam (8) of latch (9) forces the hooks (10) to engage projections (11) on the bottom sleigh, locking together the howitzer and the two sleigh members.

The tipping parts are supported and pivot in elevation on trunnion pins (3), which connect the cradle with bearings (12) in the top carriage. The equilibrators bear against the cradle at (6), and are supported in the top carriage at (7). The elevating handwheel is mounted on the top carriage at (14). Through a flexible shaft, a worm, and a worm wheel at (15), it drives a pinion (16) which is meshed with the teeth of the elevating arc. The sighting equipment is mounted on the cradle at (5). The firing base is latched to the cradle at (4) during travel, serving as a traveling lock.

The top carriage and traversing parts are supported by the bottom carriage, rotating around the pintle pin (18) which fits in the bearing (13) of the top carriage. The traversing handwheel on the left side of the top carriage is connected by means of a flexible shaft, worm, and worm wheel, to a pinion which meshes with the traversing rack (19).

The combined traveling lock and firing base *K* is hinged to the bottom carriage at (21). It is locked in firing position by a latch at (20), and in travel position at (4).

The trails are hinged to the bottom carriage at (22). The maximum spread is controlled by stops at (23), and the trails are locked in position by pins at (24). The wheel latch mechanism at (25) secures the wheel carriers.

Subcaliber Equipment.—For subcaliber practice, the top sleigh is removed, and the 37-mm. Subcaliber Mount, M5, is installed on top of the howitzer. It is held in position by hooks which engage projecting lugs on the bottom sleigh.

255. The 155-mm. Howitzer.—The partial modernization of World-War types of matériel, by converting the carriages for high-speed trans-

port, is exemplified by the 155-mm. Howitzer Carriage, M1918A1, shown in Fig. 173. The modification included replacement of the old wooden wheels by disc and rim wheels mounted on roller bearings, installation of air brakes, changes in the axles, installation of new towing

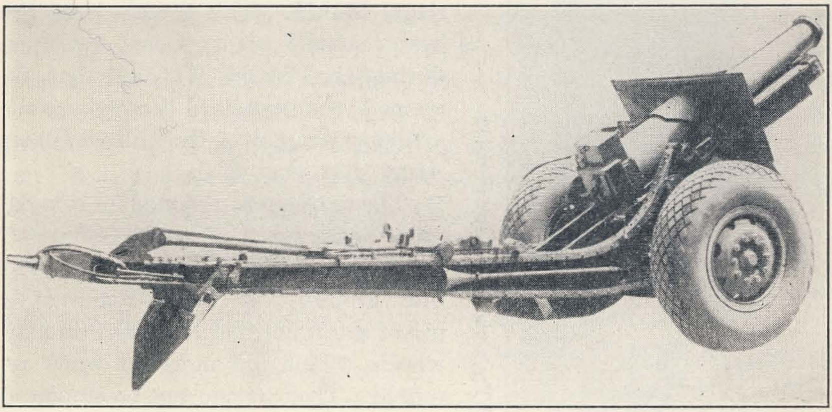


FIG. 173.—155-mm. Howitzer Carriage, M1918A1.

drawbar, and addition of traveling locks. The carriage travels on heavy-duty bus balloon pneumatic tires, with puncture-sealing inner tubes.

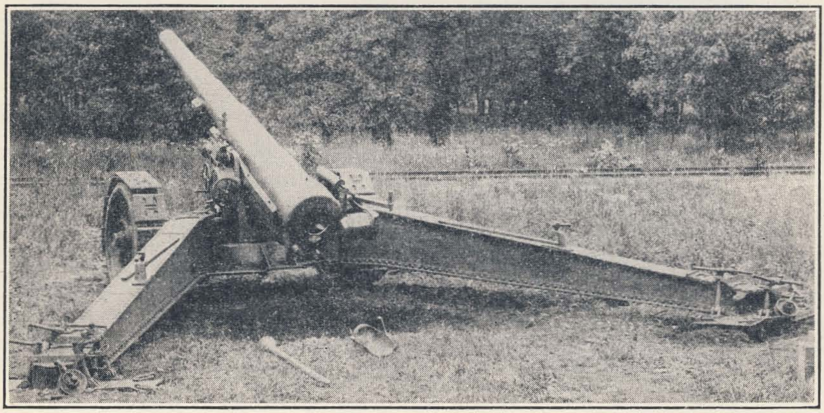


FIG. 174.—The 155-mm. Gun (G. P. F.) in Firing Position.

The firing characteristics of this matériel are unchanged. The maximum traverse and elevation are 6° and 42°, respectively. The howitzer has a muzzle velocity of 1480 f. s., firing a 95-lb. H. E. Shell to a range of

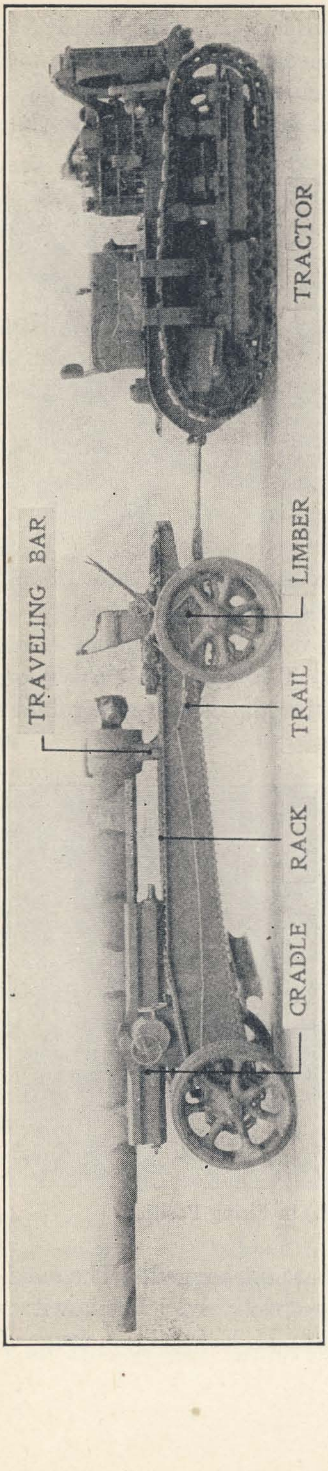


FIG. 175.—155-mm. Gun Carriage, Limber, and Tractor. Traveling Position.

12,400 yd. The use of the breech counterweight to permit trunnioning closer to the breech has been discussed in a previous section.

256. The 155-mm. Gun and Carriage, M1918.—This is considered the best matériel of its class developed during the World War. It has remained the standard heavy mobile artillery weapon of the United States Army since that time.

The carriage is designed for a maximum road speed of about 8 m. p. h., towed by a truck or tractor. The unit ground pressure is reduced by use of caterpillar treads on the carriage wheels, which are installed when required. The carriage can be emplaced in about 30 minutes. It permits 35° gun elevation and 60° traverse. The gun fires a 95-lb. H. E. Shell, at a muzzle velocity of 2410 f. s., to a maximum range of 17,400 yd.

For harbor defense use, the carriage is mounted on a concrete emplacement, which is designed to provide for the wider field of fire necessary. The trail ends ride on a circular rail embedded in the concrete, which facilitates the making of large changes in azimuth and provides necessary stability in firing by taking the horizontal and vertical components of the firing forces at the trail ends.

The Gun.—The gun is of the built-up type, illustrated by Fig. 176. It comprises a tube, a jacket over the rear end, a breech ring screwed to the rear of the jacket, hoops *A* and *B*, which extend well towards the muzzle, and necessary securing rings and screws. The piston rods of the recoil

mechanism are attached to a recoil lug at the bottom of the breech ring. The gun is supported by four bronze guide clips on each side which engage corresponding slots machined in the cradle.

The breechblock is of the slotted screw type, screwed into and supported by a block carrier, which swings horizontally on a hinge pin. As the operating lever, Fig. 177, is pulled to the rear, it actuates a straight rack sliding within the carrier; the rack is meshed with a toothed segment on top of the block, rotating it the distance necessary to disengage the interrupted threads and unlock the breech. The lever, rack, block, and carrier are then locked together, and swing as a unit on the hinge pin. A spring-actuated breechblock counterbalance is provided. At

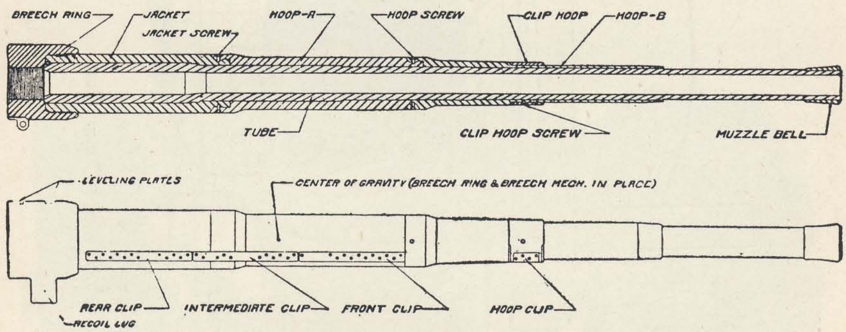


Fig. 176.—155-mm. Gun, Model 1918 (Filloux).

high firing angles, its operation assists in closing the breech and it also retards the swing in opening.

Separate loading ammunition is employed, the powder charge being in a cartridge bag. Obturation is accomplished by use of the conventional obturator, comprising a mushroom head, asbestos gas-check pad, and split rings.

The firing mechanism, containing a 21-grain percussion primer, is screwed into a housing at the rear end of the obturator spindle. A percussion hammer unit, operated by a pull of the lanyard, strikes the firing pin to fire the primer. After the round is fired, the firing mechanism is readily unscrewed and removed; it is replaced when a new primer has been inserted, or a spare unit is used for the next round.

The Carriage.—The operations required to change the gun from the traveling to the firing position are described below in the order in which performed:

(1) To change from its traveling position to its firing position, the gun is moved forward. It is held in the traveling position by an assembly known as the *traveling lock.* This assembly consists of a U-beam

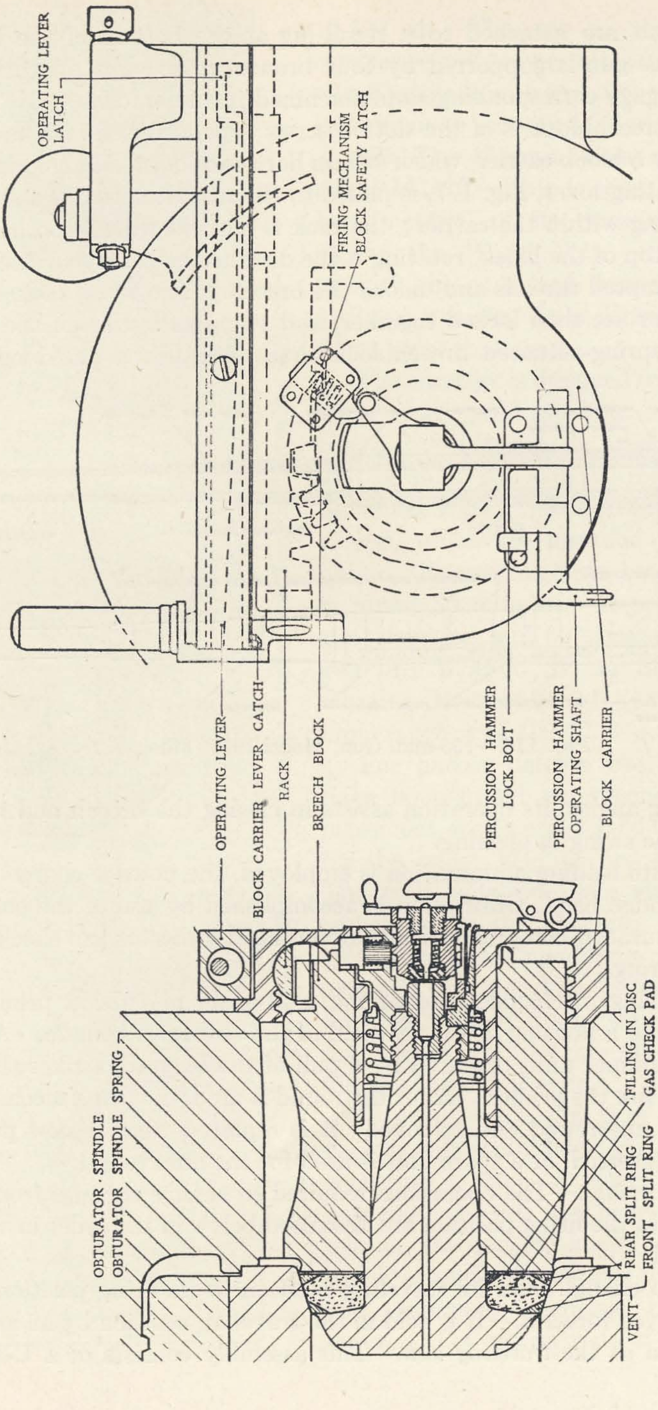


FIG. 177.—Breech Mechanism, 155-mm. Gun.

called the *traveling bar* (Fig. 175) straddling the two trails, with locking clamps at each end. The gun is locked to the middle of the traveling bar. The ends of the bar in the traveling position are locked to the trails. Each end is also geared to racks which extend forward along the top side of the trails. By simultaneously operating the pinion gears on the racks, the gun is moved forward and attached to the recoil mechanism. The traveling lock assembly is then removed.

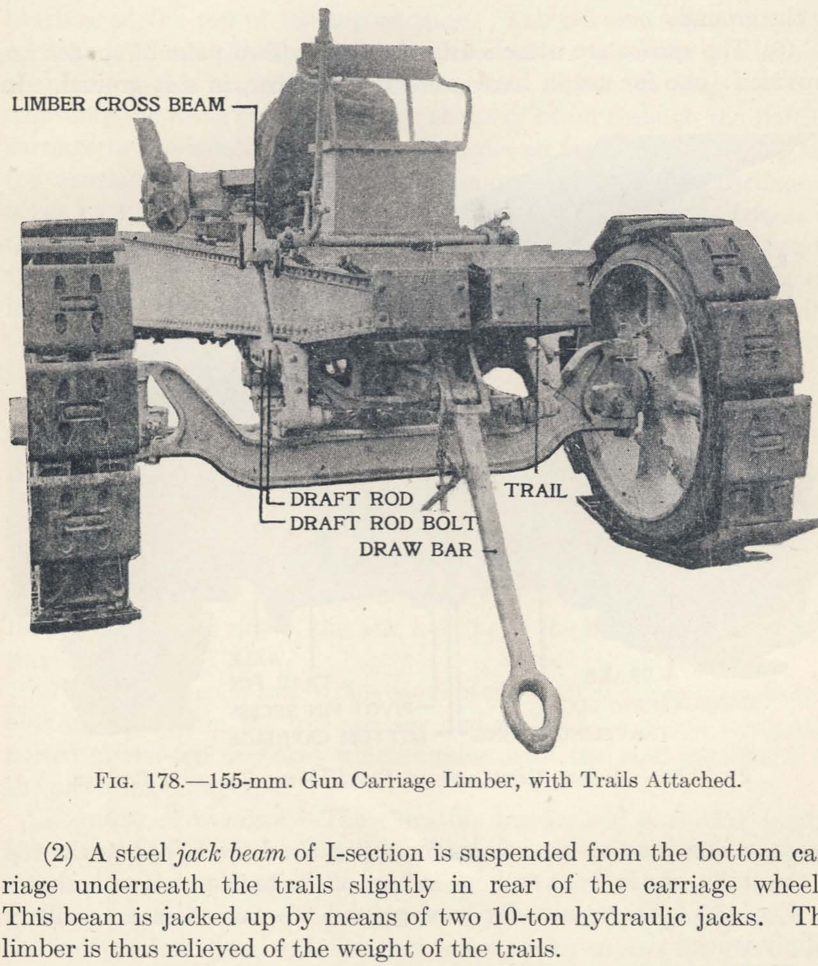


FIG. 178.—155-mm. Gun Carriage Limber, with Trails Attached.

(2) A steel *jack beam* of I-section is suspended from the bottom carriage underneath the trails slightly in rear of the carriage wheels. This beam is jacked up by means of two 10-ton hydraulic jacks. The limber is thus relieved of the weight of the trails.

(3) The limber is then removed. The limber, shown in Fig. 178, consists only of the wheels, axle, drawbar, and attached parts. The trails are locked to the limber by the *limber cross beam* and the two *draft rods* which in the traveling position are drawn up tightly. To

unlimber, the draft rods are loosened and slipped over the *draft rod bolts*. The limber then may be moved to the rear, free from the trails.

(4) The *trails* are spread, sliding along the jack beam. They are pivoted by steel pins in bosses in the sides of the bottom carriage and have a horizontal movement of about 30° each. After opening, they are fixed by *trail pins* fitting in notches at the extreme forward ends of the trails, as shown in Fig. 179.

(5) The *jack beam* is lowered until the ends of the trails are close to the ground.

(6) The *spades* are attached to the trail. Two pairs of spades are provided: one for use in hard ground; the other, in soft ground. In

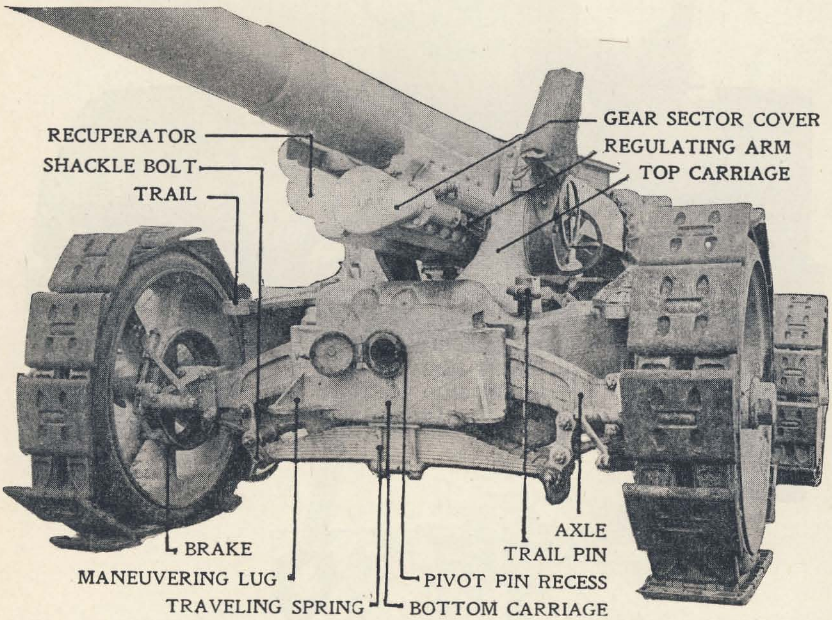


FIG. 179.—155-mm. Gun Carriage, Front View. Traveling Position.

the traveling position the spades for soft ground are lashed to the top of the trails, one in front and one in rear of the brakeman's seat, shown on Fig. 175. The spades for hard ground are carried in an artillery supply truck.

(7) The jack beam is lowered until the spades receive ground contact; jack beam and jacks then are removed.

(8) Jacks are placed under the two *front maneuvering lugs* (Fig. 179) and the carriage is raised slightly to release the weight from the trav-

eling spring. *Shacklè bolts* are removed and re-engaged in shackles when the spring is clear. A large steel *axle pivot pin* is then inserted in the axle pivot pin recess, thus connecting the axle to the bottom carriage.

Top Carriage.—The top carriage is a large steel casting mounted and traversing on the bottom carriage. The handwheels, driving gears, and shafting of the elevating and traversing mechanisms are mounted on the top carriage. The tipping parts of the carriage (supporting the gun in the cradle) are pivoted through the cradle trunnions, in two bearings at the top of the top carriage. The bottom face of the top carriage is a large elliptical bearing surface which, when the gun is fired, bears full upon a corresponding surface of the bottom carriage and thus transmits the firing stresses and the shock of recoil through the bottom carriage to the wheels and trails. In order to facilitate traversing the top carriage, the weight of the gun, tipping parts, and top carriage is borne on a small steel socket bearing and not on the bearing surfaces of the top and bottom carriages. This small bearing supports the weight through eight Belleville springs assembled in a box suspended beneath the bottom carriage. When the gun is fired the springs deflect, permitting the large bearing surfaces of the bottom and top carriages to receive the full impact of the firing stresses.

Bottom Carriage.—The bottom carriage, shown in Fig. 180, is a large steel casting suspended from the axle by a multiple leaf spring (in the traveling position). The bottom carriage supports the top carriage, houses and retains the axle in its correct position, and provides hinge connections for the trail members. In the firing position it is connected directly to the axle by the axle pivot pin. The axle pivot pin then provides an equalizing device which compensates for differences of level. Bolted to the rear side of the axle housing of the bottom carriage is the traversing rack.

Traversing Mechanism.—This consists of a shaft and gear train assembled in bearings in the top carriage and actuating a worm (also supported in the top carriage) which meshes with the rack mentioned in the preceding paragraph.

Elevating Mechanism.—The elevating mechanism is similar to the traversing mechanism. The elevating worm meshes with a rack attached to the bottom of the cradle.

Recoil Mechanism.—The hydropneumatic recoil mechanism is of the independent type with floating piston, with means for providing variable length of recoil (Fig. 181). In this type the recoil and recuperator units function separately. The parts of the mechanism are housed within the cradle, the recoil and recuperator piston rods being attached to, and recoiling with, the gun.

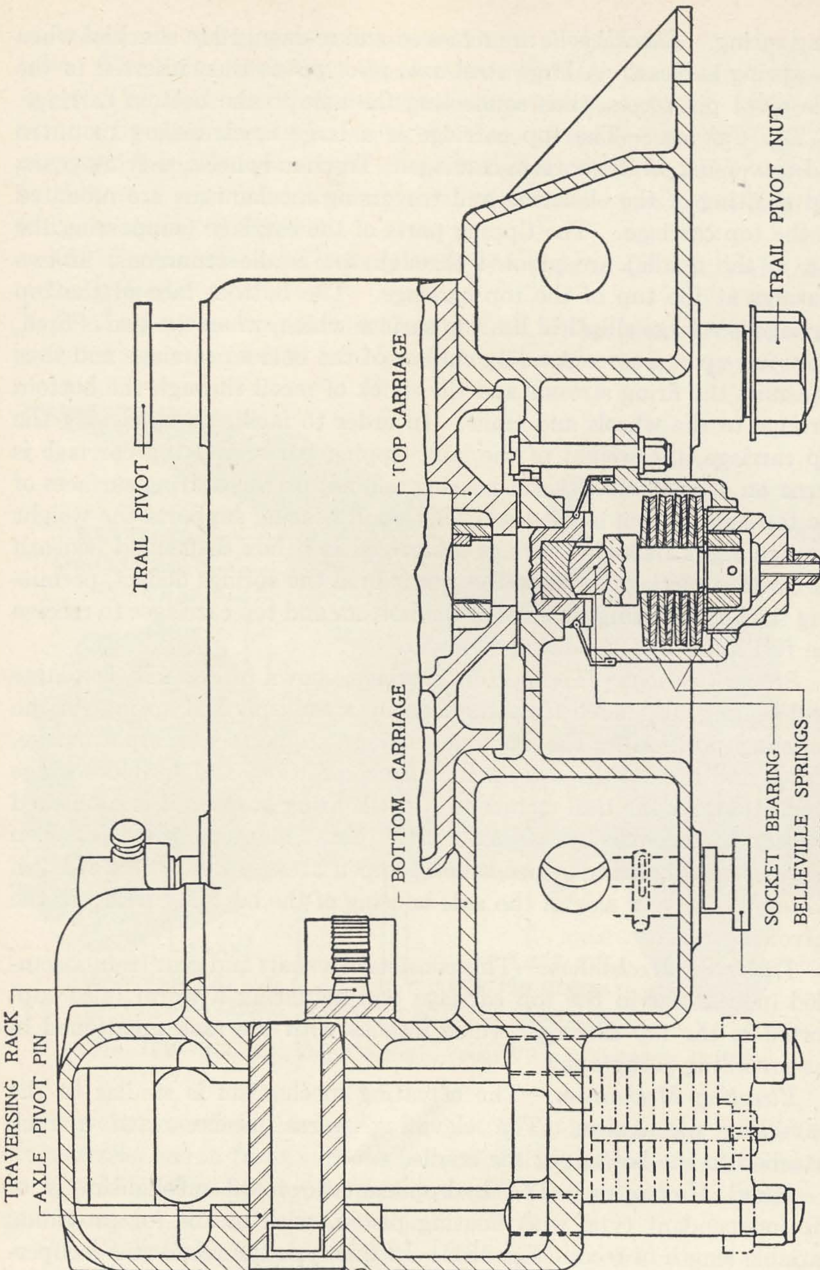


FIG. 180.—155-mm. Gun Carriage, Model of 1918 (Filloux). Bottom Carriage Assembled.

The Recoil Unit.—The recoil unit consists of four main parts:

(1) The *piston* and *hollow piston rod.* There are two large ports in the piston providing a path for flow of oil from the rear side of the piston to the forward side.

(2) The *counter rod.* This rod is located inside the piston rod. It is attached to the forward end of the recoil cylinder, can rotate but cannot move longitudinally. Four longitudinal grooves are cut along the counter rod, consisting of two long and two short grooves, arranged alternately 90° apart. The grooves vary in depth, providing a maximum orifice at the beginning of recoil and zero orifice at the end.

(3) A *counter-recoil buffer* of the dashpot type. The rear end of the counter rod is the buffer and fits the buffer chamber in the end of the

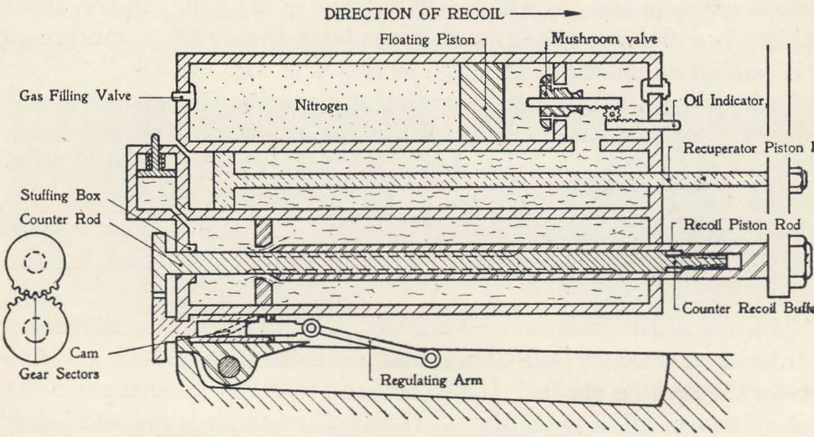


FIG. 181.—Schematic Drawing of Recoil and Recuperator Mechanism, 155-mm. Gun Carriage, Model 1918.

recoil piston rod. It is provided with two taper grooves that diminish in depth as the buffer enters the chamber.

(4) The mechanism providing variable recoil. A *regulating arm* is attached at one end to the top carriage. As the gun is elevated the relative longitudinal movement of the regulating arm and cradle is transmitted as rotary motion to the counter rod through a cam and two gear sectors.

Operation of Recoil Mechanism.—As the piston moves to the rear in recoil, oil is forced through the fixed ports in the piston. The greater part of this displaced oil moves to the forward end of the cylinder; a small quantity, however, passes to the rear to provide oil for the buffer. A variable element is introduced into the piston ports by the grooves in the counter rod. At 0° elevation, all four grooves in the counter rod are

uncovered by the piston ports and the total orifice is large. At 35° elevation, only the two short grooves are uncovered and the orifice is small. Between these two elevations, the orifice consists of the two short grooves and a varying width of the two long grooves, the width uncovered decreasing as the elevation increases.

An oil *replenisher* is connected to the recoil cylinder. It is a small oil reservoir, held under pressure by a piston and spring, and automatically provides for changes in the volume of oil in the recoil cylinder due to leakage or change in temperature.

The Recuperator Unit.—This consists of two cylinders, a small lower or oil cylinder and a large upper or gas cylinder. These two cylinders are connected by a port at the rear end. The lower cylinder contains a piston and a piston rod which is connected to the gun. In the upper cylinder is a floating piston, and a regulator containing a mushroom valve and an oil indicator, arranged as shown in Fig. 181.

Operation of Recuperator.—As the gun recoils, the piston in the lower cylinder forces the oil into the upper cylinder. The mushroom valve opens, allowing the oil to force the floating piston forward, compressing the gas. Dry nitrogen, which is noncorrosive, is used. In counter-recoil the mushroom valve is closed and the oil now returns through two 4-mm. holes in the mushroom valve, thereby throttling the action of counter-recoil.

Function of Oil Indicator.—Normally, the floating piston and regulator are separated by oil. This small oil column provides a positive stop for the floating piston. It also acts as a reservoir for changes in the total volume of oil in the system. If this oil reservoir is reduced below a certain minimum, the floating piston strikes the oil indicator rod and the finger gage outside the cylinder is drawn inward indicating a dangerous condition.

Oil leakage around the piston rod at the cylinder heads is prevented by stuffing boxes in which the packing is held under compression by Belleville springs.

257. The 155-mm. Gun Carriage and Limber, M1918A1.—This is a modification of the M1918 design, to permit towing by a prime mover at maximum road speeds of 15 m. p. h. The firing characteristics have not been modified in any way.

The modifications include the necessary alteration of wheels and axles to seat the antifriction bearings, and to permit installation of a new brake system. Electric brakes are provided, controlled from the driver's seat of the prime mover. In addition, auxiliary hand brakes are installed on the carriage wheels, for hand brake control in parking and in case it is impracticable to operate the electric brakes.

This modification illustrates the partial modernization of World-War types of matériel to increase their strategic mobility; for this transport the truck has replaced the tractor.

258. Modern Heavy Artillery.—The 155-mm. gun carriages just described permit firing elevations up to 35° only. The maximum range considered necessary in a weapon of this type cannot be obtained, and the range potentialities of the gun realized, within these elevation limits. Other improvements were desired, including greater strategic and tactical mobility, and provision for selective mounting on the carriage of either the 155-mm. gun or its companion piece the 8-in. howitzer. The new carriage embodying the improved features is illustrated in Figs. 182 and 183.

This carriage is able to mount either the gun or the howitzer; it permits 60° traverse and firing elevations up to 65°. In the traveling position, a bogie carries the weight on two axles equipped with four dual wheels, and a single-axled limber at the spade end of the trails forms the connection with the prime mover. The 155-mm. gun is disconnected from the recoil mechanism for travel, by removal of the nuts from the piston rods, and retracted until the weight of the breech end is supported by the traveling lock, as shown in Fig. 182. This is not done when the 8-in. howitzer is mounted on the carriage; it remains in its normal position in the cradle, connected to the recoil mechanism. The bogie and limber wheels are mounted on roller bearings, and are equipped with heavy-duty pneumatic tires; the mount may be towed by a prime mover at speeds of 25 m.p.h. Braking is effected by four equalized air brakes on the bogie, controlled from the seat of the prime mover. Hand brakes are provided for parking, and for use in case it is impracticable to use the air brakes.

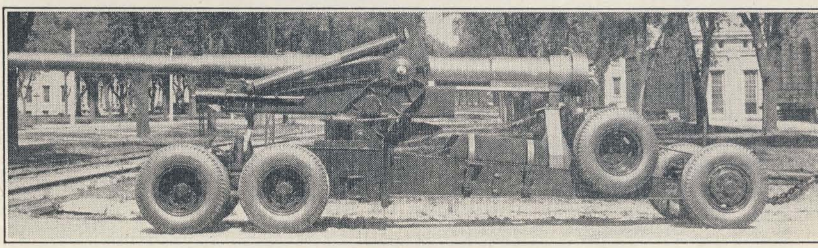


FIG. 182.—155-mm. Gun, 8-in. Howitzer Carriage, Traveling Position.

In going from the traveling to the firing position, the gun is pulled into battery by the prime mover, the piston rod nuts assembled to the rods, and the traveling lock removed. The trails are then lowered to

the ground by a lifting (lowering) screw mechanism on the limber; the limber is then removed, the trails spread to 60°, the two trail spades attached, and the two front spades attached to the bottom carriage between and outside the trails. The mount is then lowered by means of two jacks on the bogie until the bottom carriage rests on the ground; further rotation of the jacks raises the bogie clear of the ground.

The gun is supported in a cradle, which is trunnioned in bearings in the top carriage. The two equilibrators which support the unbalanced

FIG. 183.—155-mm. Gun, 8-in. Howitzer Carriage, Firing Position.

weight of the tipping parts are of the pneumatic type. The recoil mechanism, of a type similar in design to that described with the M1918 matériel, and providing varying length of recoil, is assembled in and attached to the cradle.

The top carriage supports the tipping parts and mounts the elevating and traversing mechanisms. A pintle on the bottom of the top carriage fits into a corresponding bearing in the bottom carriage. The weight of the traversing parts is supported on a double row of roller bearings on the bottom carriage. The bearings are supported on Belleville springs, which deflect when the gun is fired, so that the vertical components of the firing stresses are not transmitted through the roller bearings, but through larger bearing surfaces of the bottom and top carriages, as explained in the M1918 carriage.

CHAPTER IX

AIMING AND LAYING DEVICES

In order that a projectile may reach a given target, when fired from a gun under any given conditions, it is necessary that the gun have a certain angle of elevation and that it point in a certain azimuth. The angle of elevation will depend upon the range, the relative height of the gun and target, and the ballistic conditions. Generally, the direction in azimuth to be given the gun will be somewhat to the right or left of the direction of the target, in order to compensate for drift, wind effects, and anticipated motion of the target. The required angles of elevation and azimuth are determined beforehand, either by calculation or by estimation.

The elevating and traversing mechanisms are the means provided for moving the gun in elevation and azimuth. The aiming and laying devices are the means provided for placing the gun exactly at the predetermined angles of elevation and azimuth.

For projectiles equipped with time fuzes, it is necessary to set the fuze so that the projectile will burst at the proper point of the trajectory. For this purpose fuze setters are provided, and the operation of fuze setting may be considered as a part of the process of laying the gun.

In this chapter, the purposes and characteristics of aiming and laying devices will be discussed, followed by descriptions of a number of service types of these devices and related equipment.

259. Methods of Laying.—*Elevation.*—Guns are laid in *elevation* by one of the following methods:

(*a*) The required angle in a vertical plane between the axis of the bore of the gun and the optical axis of the sight is determined and set on the sight by means of appropriate scales. The desired laying is obtained by moving the gun in elevation until the horizontal line (cross hair) of the sight is directed on the target.

(*b*) The required angle in a vertical plane between the axis of the bore of the gun and a horizontal plane is determined and set on a quadrant or similar device attached to the gun. The desired laying is obtained by moving the gun in elevation until the bubble of the level vial of the quadrant is centered.

(*c*) When guns are mounted on level platforms, the required angle in a vertical plane between the axis of the bore of the gun and a horizontal plane may be indicated on a range disc, drum, or slide, which may be graduated in range or angular units. The desired laying is obtained by moving the gun in elevation until the graduated scale indicates the proper value.

Direction.—Guns are laid in *direction* by one of the following methods:

(*a*) The required angle in a horizontal plane between the axis of the bore of the gun and the optical axis of the sight is determined and set on the sight by means of the deflection scale. The desired laying is obtained by moving the gun in azimuth until the vertical line of the sight is directed on the target.

(*b*) A convenient aiming point is selected. The horizontal angle between the lines *gun-target* and *gun-aiming point*, corrected for drift, wind effects, etc., is determined and set on the deflection scale of the sight. The desired laying is obtained by moving the gun in azimuth until the vertical line of the sight is directed on the aiming point.

(*c*) When guns are mounted on level platforms, the required angle in a horizontal plane between the axis of the bore of the gun and some vertical reference plane, as the meridian plane, may be indicated on an azimuth circle on the base ring of the carriage. The desired laying is obtained by moving the gun in azimuth until the proper angle is indicated on the azimuth circle.

Various combinations of the methods of laying in elevation and direction are possible. Of these combinations the following, listed under their usual designations, are employed:

Case I.—In which both direction and elevation are given by means of the sight.

Case IA.—In which direction is given by means of the sight, and elevation is given by a combination of the sight and an elevation scale or graduated drum.

Case II.—In which direction is given by means of the sight, and elevation is given by means of an elevation scale or quadrant.

Case III.—In which direction is given by means of an azimuth scale, and elevation is given by means of an elevation scale or quadrant.

When a gun is laid in both direction and elevation by sighting directly upon the target, the method is known as direct laying. For fire at rapidly moving targets, direct laying generally is employed.

When a gun is laid in direction by sighting on an object other than the target, and elevation is set off on a range drum, quadrant, or similar device, the method is known as indirect laying. Indirect laying is the predominating method for field artillery. It permits effective fire from

concealed positions, eliminates possible errors in target identification, and affords decided advantages of collective control of firing.

260. Graduations of Laying Devices.—The scales of the laying devices generally are graduated in units to correspond to those used in the computations and adjustments of firing data. Frequently the *mil* is used as a unit of angular measure. A *mil* is 1/6400 of a circle. To facilitate rapid computation, it may be assumed as an angle which, at any range, subtends a distance of 1/1000 of the range.

In general, scales on sights, azimuth circles, and quadrants for seacoast mounts are graduated in degrees, and those for mobile artillery in mils. Railway mounts are equipped with sights graduated in mils and, in some cases, in degrees also for use in firing on naval targets.

For ammunition having a given type and weight of projectile and with powder charges adjusted to give standard muzzle velocity, the range attained under normal atmospheric conditions with a given angle of elevation is fixed. Hence, for weapons using a single standard type of ammunition, the devices for laying in elevation may be graduated directly in range. This method of graduating facilitates a rapid rate of fire and, in consequence, is used on rifle and machine gun sights and range scales of rapid-firing field pieces. In fixed emplacements, having a known height above the datum plane, corrections for the known height and for the curvature of the earth may be incorporated with firing-table elevations, permitting range scales to be graduated in terms of corrected range.

When devices for laying in elevation are graduated in terms of range, provision must be made for firing with types of ammunition other than that pertaining to the graduations. With large caliber cannon this is done either by providing a separate drum for each type of ammunition and zone of fire or by using a range-relation scale. With most field carriages, range scales, dials, and drums have graduations both in range and angular units. With small arms weapons, only range graduations appropriate for ball cartridges are employed; for other types of cartridges, the muzzle velocities are adjusted to give the same range at a certain sight setting as the ball cartridge; at other sight settings, the ranges are only approximately correct.

The accuracy of a laying device may be specified in terms of the unit of graduation of its scales. As a general rule, the permissible error at any setting should not exceed plus or minus one-half the unit of graduation. However, the accuracy of the device is not determined by the graduations of its scales, but by its optical and mechanical functioning. The accuracy of a sight is not increased merely by increasing the number of divisions of its scales; it is necessary, in addition, to

adjust the optical and mechanical components to reduce the errors to practicable minima.

The usual method of setting angular values on sighting devices is illustrated schematically in Fig. 184. One complete revolution of the drum *D*, operating through a worm and worm-wheel segment, changes the angular relation of the parts *A* and *B* by 100 units, indicated on the upper scale. A smaller or larger change is indicated by the reading on the upper scale combined with that on the drum. Settings by this method are more rapid and less subject to personal errors than those made by the use of a vernier.

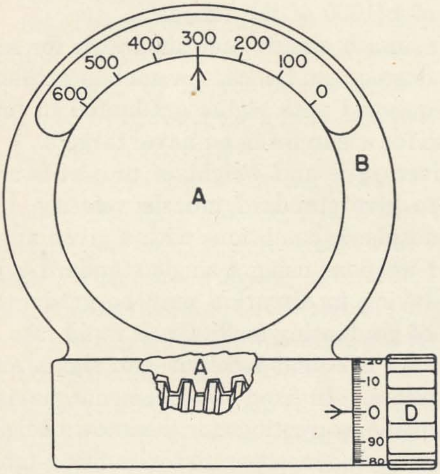


FIG. 184.—Method of Setting Angular Values.

261. Correction Devices.—In general, corrections for drift, wind effects, and other variations from ballistic conditions assumed as standard are determined and applied to the computed angles of deflection and elevation to obtain corrected values of these angles to apply to the aiming and laying devices.

The deviation of the projectile due to drift results from its rotation imparted by the rifling of the gun. In most service guns the drift is to the right and increases with the range. Sights of small arms weapons incorporate automatic correction for drift; the rear sight is constructed so that, as the peep is raised in elevation to any range, it is moved horizontally just enough to compensate for drift at that range. For some intermediate caliber weapons, as exemplified by a sight for tank guns, the horizontal cross hair of the sight is moved with the range setting and the other cross hair is fixed and inclined slightly from the vertical; the intersection of the two cross hairs is so positioned as to correct for drift corresponding to any given range setting. The 75-mm. Gun Carriage, Model 1917 (British), was designed with one trunnion higher than the other to compensate for the effects of drift. In general, however, sights for artillery weapons have no provisions for automatic compensation for drift, the reason being that such provisions would make corrections applicable only to a particular type of ammunition.

Firing data are computed under the assumption that the gun carriage

is level, the angle of deflection being measured in a horizontal plane and that of elevation in a vertical plane through the axis of the gun. If the carriage is not level, because of unevenness of the ground or similar conditions, the computed firing data, applied to a sighting device bearing a fixed relation to the gun carriage, would not result in the desired laying. To avoid such errors caused by the inclination of the axis of the trunnions from a horizontal plane, without having to resort to complicated computations, most sight and telescope mounts include mechanisms for both cross and fore-and-aft (longitudinal) leveling. Consider the telescope mount illustrated in Fig. 185. In order to indicate cor-

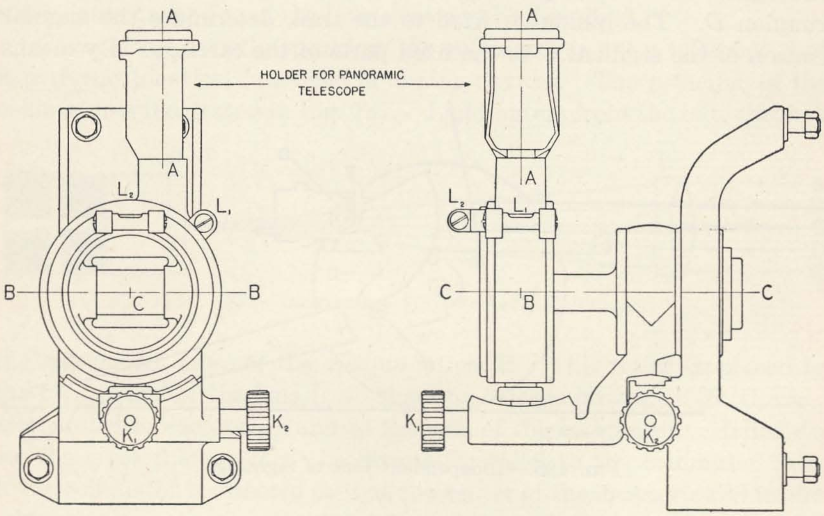


FIG. 185.—Leveling Devices.

rectly angles in a horizontal plane, the axis AA of a panoramic telescope mounted in the holder must be vertical. Since the telescope mount is bolted to the carriage, any unevenness of the ground would cause a variation of the axis AA from the vertical. A *cross-leveling* device, consisting of a worm and worm wheel actuated by the knob K_1 is provided to rotate the sight mount about the axis BB until the bubble of the level L_1 is centered. A similar *fore-and-aft leveling* device, actuated by the knob, K_2, rotates the mount about the axis CC until the bubble of the level L_2 is centered. With both bubbles centered, the axis AA is vertical.

262. Independent Line of Sighting.—In order to relieve the gun pointer of the entire responsibility of laying, most rapid-fire field guns are provided with a system known as the *independent line of sighting.*

This provision allows the division of the responsibilities of laying, permitting an increased rate of fire and more convenient methods of adjusting fire. The actual quadrant elevation of the gun consists of two parts: first, the elevation necessary to reach the target when both gun and target are at the same height; and, second, the increase or decrease in elevation corresponding to the difference in height between gun and target (angle of site). With the independent line of sighting, these two parts of the quadrant elevation are applied to the piece independently and by different cannoneers.

Consider the arrangement represented schematically in Fig. 186. The sight is fixed to the gear segment C, which rotates about the cradle trunnion D. The pinion A, fixed to the trail, determines the angular relation of the segment C to the fixed parts of the carriage. By means

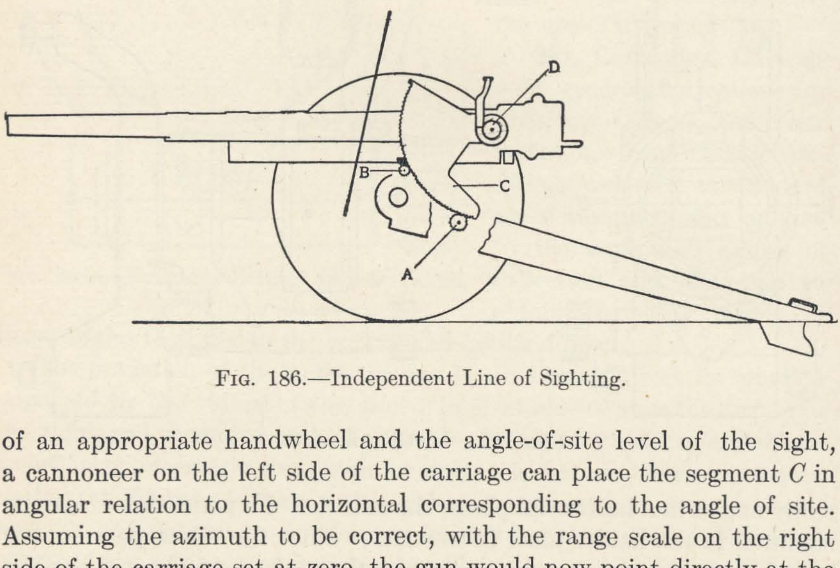


FIG. 186.—Independent Line of Sighting.

of an appropriate handwheel and the angle-of-site level of the sight, a cannoneer on the left side of the carriage can place the segment C in angular relation to the horizontal corresponding to the angle of site. Assuming the azimuth to be correct, with the range scale on the right side of the carriage set at zero, the gun would now point directly at the target. A handwheel on the right side of the carriage actuates both the range scale and the pinion B, fixed to the cradle, so as to provide additional elevation to the gun corresponding to the range indicated. Hence, another cannoneer on the right side of the carriage can operate the elevation handwheel to set the range scale at the proper elevation, thus elevating the axis of the bore the additional amount necessary to make the trajectory pass through the target.

For any given target, the cannoneer on the left has only to maintain his sight on the target or aiming point in azimuth and the bubble of the angle-of-site level centered. Ranges are set by a cannoneer on the

right side of the carriage, and changes in range do not affect the laying operations on the left side of the carriage.

There are several other methods of securing the independent line of sighting, differing from the one illustrated in application but not in principle.

263. Telescopes.—There are a great variety of telescopes used in sighting systems, differing in optical and mechanical features. The large number of types results from attempts to produce telescopes with optical characteristics exactly suited to anticipated uses and mechanical constructions, particularly types of graduations, in conformity with the methods of laying employed. However, the optical systems in all these types come under one of the four classes to be described.

Collimator.—Strictly speaking, the collimator is not a telescope, but it performs identical functions in aiming devices. The principle of the collimator is illustrated in Fig. 187. Light enters from the left, through

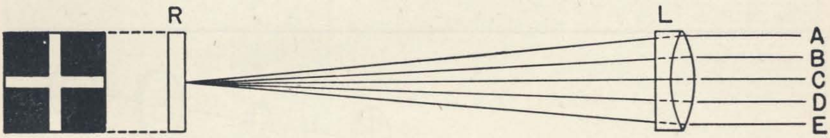


FIG. 187.—Diagrammatic Sketch of a Collimator.

the translucent cross of the opaque reticle *R*. This reticle is placed in the focal plane of the lens *L*, so that the emerging rays, *A*, *B*, *C*, etc., are parallel to each other and to the axis of the collimator. Hence, to see the cross the eye must be directed parallel to the collimator axis. If the collimator is directed so that the center of the cross, viewed in the collimator, appears to coincide with an object, viewed over or to the side of the collimator, the axis of the collimator should pass through the object. Collimators are simple, compact, and inexpensive; they have proved sufficiently accurate within the ranges of light artillery, but provide no optical assistance to the eye in viewing indistinct and distant targets.

Straight Telescope.—The optical systems of the two types of straight telescopes are illustrated in Figs. 188 and 189. The system employing the lens erecting system is used to advantage where the diameter of the telescope tube must be held to the minimum, consistent with a given field of view; it is used in telescopic rifle sights. The system employing the Porro prism erecting system is used to advantage where the diameter of the telescope tube may be comparatively large, but the length of the tube is restricted; it is used extensively in sighting systems for seacoast and railway weapons. The principal advantages of the straight tele-

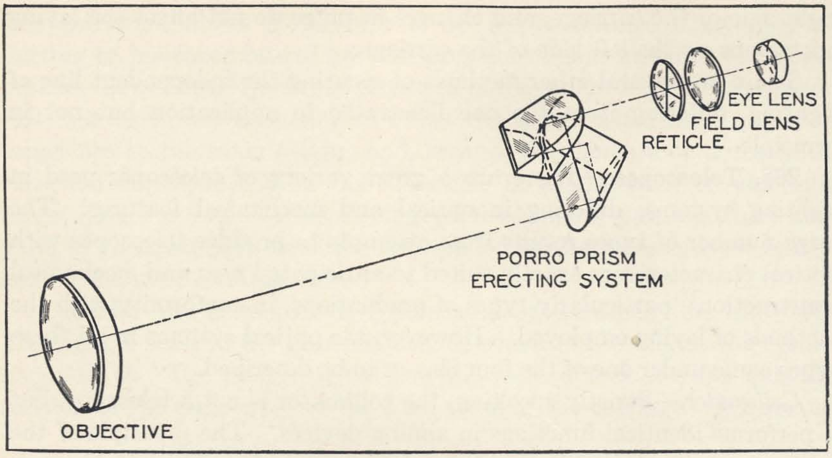


FIG. 188.—Telescope with Prism Erecting System.

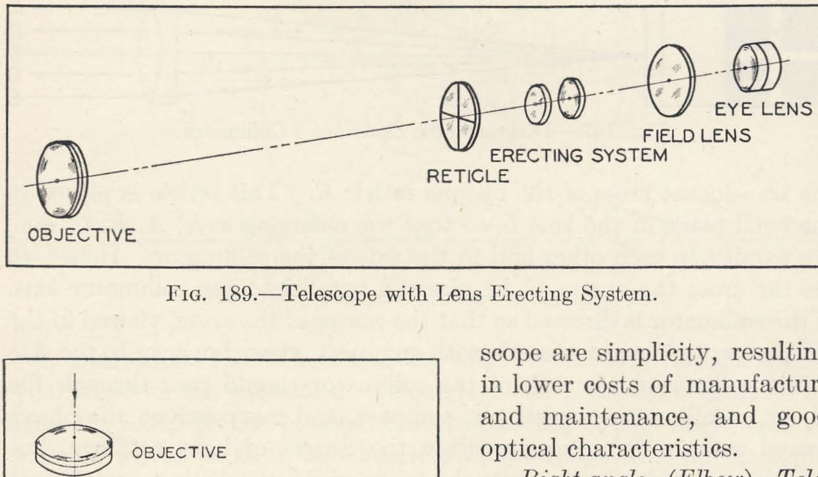


FIG. 189.—Telescope with Lens Erecting System.

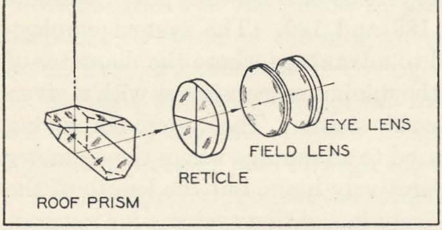


FIG. 190.—The Right-angle Telescope.

scope are simplicity, resulting in lower costs of manufacture and maintenance, and good optical characteristics.

Right-angle (Elbow) Telescope.—The optical system of the right-angle telescope, shown in Fig. 190, is similar to that of the straight telescope, except for the erecting system. In addition to performing the function of an erecting system, the roof prism bends the axis of the telescope. The right-angle telescope is a particular

type of elbow telescope having the axis bent at 90°. The disadvantage of this system is the difficulty of manufacturing the roof prism; any variation of the roof angle from 90° produces secondary images to make the definition less distinct. This type of telescope is used to

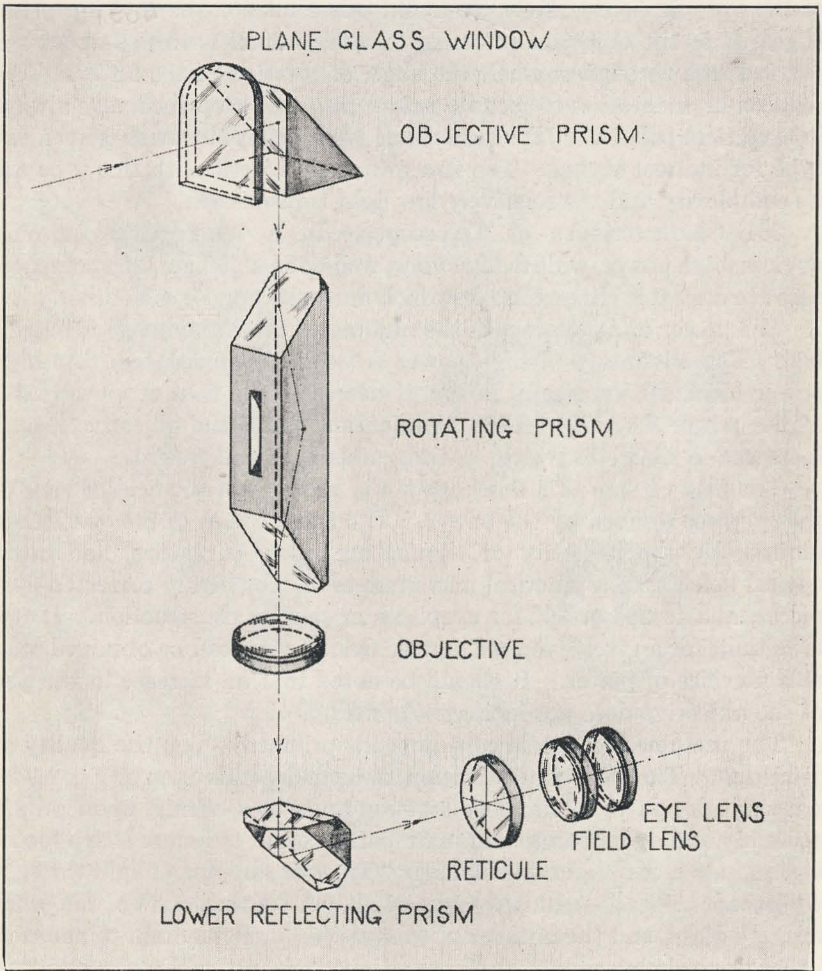


FIG. 191.—The Panoramic Telescope.

advantage where it is impracticable for the observer to place his eye in prolongation of the axis of a straight telescope.

Panoramic Telescope.—The optical system employed in panoramic telescopes is shown in Fig. 191. It may be considered as the optical

system of the right-angle telescope, to which has been added the rotating and objective prisms. By means of an attached azimuth scale, the objective prism may be rotated about the vertical axis through any desired angle. If the rotating prism remained fixed, the image seen by the eye would be rotated through a corresponding angle about the axis of the eye and field lenses. To avoid this condition the rotating prism is geared to the objective prism so that the former is turned about the vertical axis through one-half the angle of rotation of the latter. This relation in orientation of the two prisms serves to keep the image always in a vertical position. The panoramic telescope is the most convenient type for indirect laying. The two principal objections to this type are its complexity and the relatively low light transmission.

264. Characteristics of Telescopes.—In a telescope for aiming devices, high power, wide field of view, well-defined images, and compactness are desirable characteristics which mutually oppose each other.

The power of a telescope is the number of times the image is magnified. The advantage of high power is frequently overrated. As high power increases the size of image, it decreases the field of view. Also higher power inversely affects illumination unless the objective lens is increased in diameter which, in turn, adds bulk and weight.

The field of view of a telescope is the quotient of the field of view of the eyepiece divided by the power. The field of view of the eyepiece is limited, by the necessity of eliminating color, curvature, and other optical defects, to a practical maximum of 45° for highly corrected eyepieces, and to 25° or 30° for eyepieces of simpler construction. It follows that, for a given eyepiece, a wide field of view can be obtained only at a sacrifice of power. It should be noted that an increase in the size of the objective does not increase the field of view.

The usefulness of a telescope depends primarily upon the quality of definition. The quality of definition, in turn, depends upon proper materials and design to eliminate distortion and color effects, upon proper assembly and operation to eliminate parallax and to secure sharp focusing, and upon the brightness of image. The transmission of light through a telescope depends upon the types of glass used, the length of the paths through glass, and the number of changes from one medium to another. Other things being equal, the illumination is proportional to the quotient of the area of the full aperture of the objective divided by the square of the power. In order to give as much light as it is possible for the eye to use, the telescope should be designed so that the exit pupil, which is the emerging light, should have a diameter equal to that of the pupil of the eye; with a larger exit pupil, light is wasted. The diameter of the pupil of the eye varies under different conditions of illumination. For

this reason telescopes for night use generally vary in design from those intended for day use.

265. Sight for Infantry Mortar.—Fig. 192 shows the Sight, M2A3, for the 81-mm. Mortar, M1. This sight is a combination of collimators and elevation quadrant to lay the mortar in azimuth and elevation. The sight is attached by means of the bracket (1), which fits a socket on the yoke of the mortar and is secured by the latch (2). The sight is in the normal or vertical position with the mortar at 45° elevation. The collimator (3), azimuth scale (4), and azimuth micrometer (5) provide the means required for laying at the desired azimuth. Large changes in

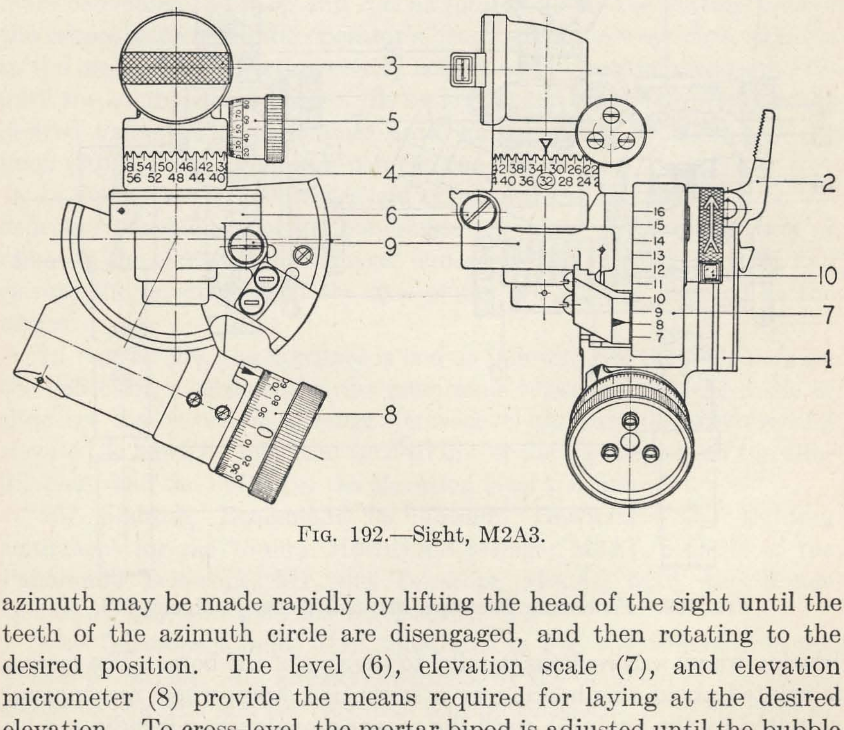


Fig. 192.—Sight, M2A3.

azimuth may be made rapidly by lifting the head of the sight until the teeth of the azimuth circle are disengaged, and then rotating to the desired position. The level (6), elevation scale (7), and elevation micrometer (8) provide the means required for laying at the desired elevation. To cross-level, the mortar bipod is adjusted until the bubble of the level (9) is centered. A fixed collimator (10) is used to determine the minimum elevation at which the trajectory will clear objects in the immediate foreground.

266. Sighting Equipment for Pack Howitzer.—The sighting equipment for the 75-mm. Pack Howitzer Carriage, M1, illustrated in Fig. 193, consists of the Panoramic Telescope, M1, and the Telescope Mount, M3. The panoramic telescope is attached to and remains integral with the telescope mount. The mount is attached to the left side of the

carriage by inserting the support (1) into a socket on the carriage cradle. The lug (2) positions the mount in relation to the axis of the bore. The bracket (3) slides over the upper portion of the support (1) and is secured in either a high or low position by the clamping device (4).

The mount consists of the cross-leveling, elevation, and angle-of-site mechanisms.

The cross-leveling mechanism is located compactly within the body of the mount. At the outer end of the bracket (3) there is a

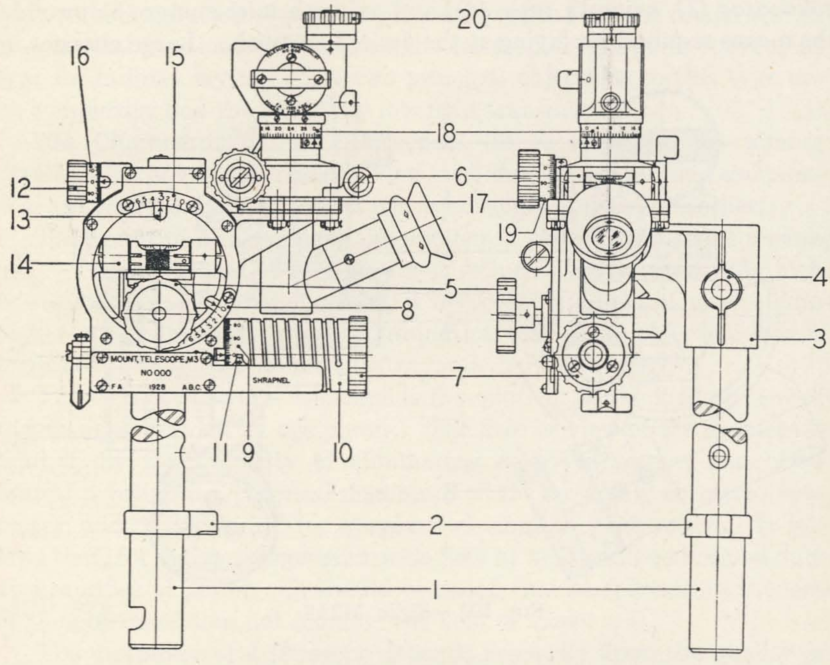


FIG. 193.—Panoramic Telescope, M1, and Telescope Mount, M3.

bearing whose axis remains parallel to the axis of the bore. The mount is rotated about this bearing by a worm and worm-wheel mechanism, actuated by the knob (5), until the proper cross-leveling is indicated by the level (6).

The elevation mechanism is actuated by the knob (7) to rotate the body of the mount and attached panoramic telescope about a horizontal axis until the desired elevation is indicated by the combined readings of the scale (8) and drum (9), or the desired range is indicated by the reading on the helical drum (10) opposite the sliding index (11). The range graduations, which are not shown in the figure, are applicable to only one type of ammunition.

The angle-of-site mechanism is actuated by the knob (12) to cause the index (13) and the level (14) to rotate in relation to the mount until the desired angle of site is indicated by the combined readings of the scale (15) and drum (16). The normal setting of the angle-of-site scale is 300 to avoid the use of plus and minus values.

For given settings of the elevation and angle-of-site mechanisms, the level (14) is rotated in a vertical plane until its angular relation to the axis of the bore corresponds to the combined values of the two settings.

The telescope is similar to the usual type of panoramic telescope, except that the eyepiece is inclined 25° from the horizontal to provide a more convenient position and can be rotated about the vertical axis of the telescope to move the operator's head out of the way when sighting to the rear. The deflection setting is obtained by turning the knob (17) until the combined readings of the scale (18) and drum (19) indicate the desired value. The panoramic head can be tilted by means of the knob (20) to keep the aiming point in the field of view.

In *direct fire*, the howitzer is laid as follows: Set the deflection on the deflection mechanism of the panoramic telescope; set the elevation or range on the elevation mechanism; cross-level the mount; traverse and elevate the howitzer until the axis of the telescope is directed at the target.

In *indirect fire*, the howitzer is laid as follows: Set the deflection on the deflection mechanism of the panoramic telescope; set the angle of site; set the elevation or range; cross-level the mount; traverse and elevate the howitzer until the vertical line of the telescope is on the aiming point and the bubble of the elevation level is centered.

267. Sighting Equipment for 75-mm. Howitzer.—The sighting equipment for the 75-mm. Howitzer Carriage, M3A1, consists of the Panoramic Telescope, M1, the Telescope Mount, M16, the Range Quadrant, M3, and the Elbow Telescope, M5.

The Telescope Mount, M16, illustrated in Fig. 194, differs from the Telescope Mount, M3, already described, by the omission of the angle-of-site mechanism and the elevation and range scales. The operator of the panoramic telescope and mount, on the left side of the carriage, lays the howitzer only in azimuth.

The Range Quadrant, M3, illustrated in Fig. 195, is mounted on the right side of the carriage and contains all the provisions for laying the howitzer at the proper elevation, in the manner described for the Telescope Mount, M3. For *direct fire*, the Elbow Telescope, M5, is mounted in the clamp (1) on top of the quadrant and used to lay the howitzer in elevation. In order that the deflection angle, set by the operator on the left side of the carriage, will not cause the target to move

laterally out of the field of view of the elbow telescope, a limited movement in deflection can be made by turning the knob (2).

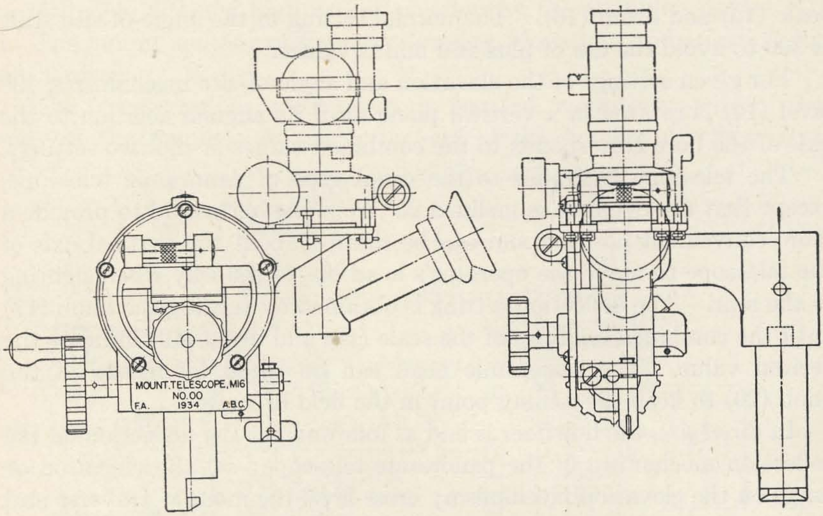


FIG. 194.—Telescope Mount, M16.

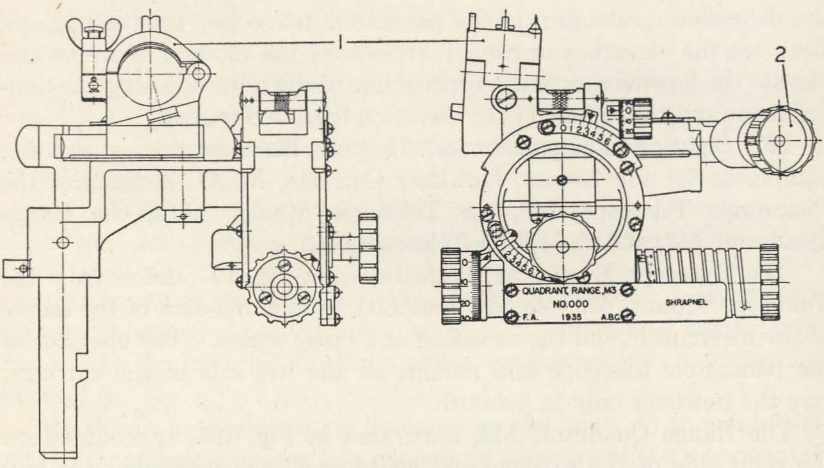


FIG. 195.—Range Quadrant, M3.

268. Sighting Equipment for 75-mm. Gun.—The sighting equipment for the 75-mm. Gun Carriage, M2, consists of the Panoramic Telescope, M5, the Telescope Mount, M15, and the Range Quadrant, M1.

In the firing position, the Panoramic Telescope, M5 (Fig. 196), is mounted in the holder at the top of the Telescope Mount, M15

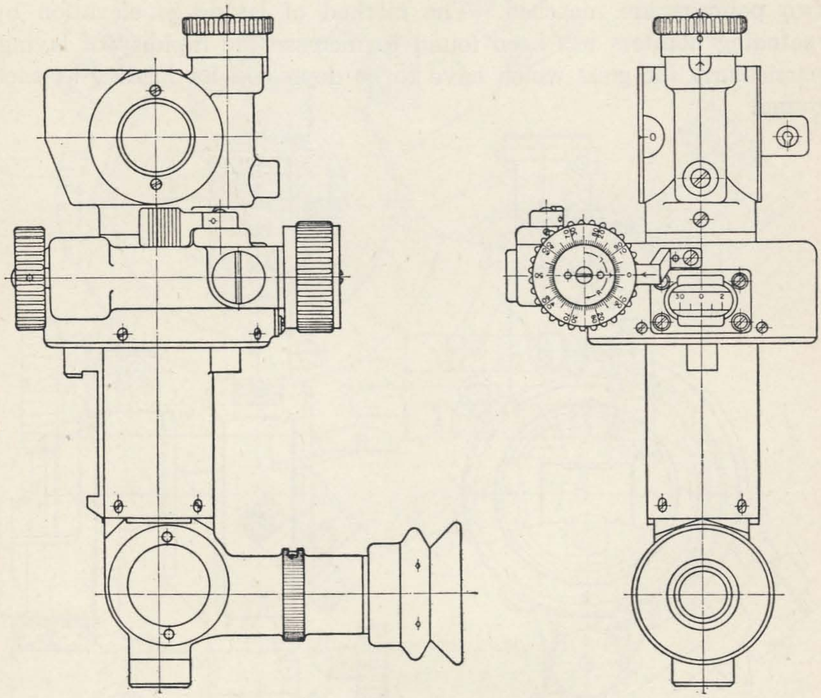


FIG. 196.—Panoramic Telescope, M5.

(Fig. 197), the latter being attached to the left side of the carriage. The telescope is provided with an azimuth mechanism and the head can be tilted to keep the aiming point in the field of view.

The telescope mount provides for both cross- and fore-and-aft leveling. To avoid damage in case the carriage should be overturned accidentally, the holder for the panoramic telescope can be rotated forward through 90° to a traveling position.

The Range Quadrant, M1, shown in Fig. 198, is mounted over the right trunnion and provides the means for laying the gun at the desired elevations. To lay the gun at a particular elevation, the angle of site is set on the scale (1) and drum (2), the elevation is set on the scale (3) and drum (4), or the range is set on the helical scale (5), and the bubble of the level (6) is centered by means of the knobs (7 or 8). These operations serve to displace the pointer (9), which is on an arm integral with the body of the quadrant, from its normal position by an angular

amount equal to the desired elevation. A second pointer (10) is on another arm, in rear of the first, which moves with the gun in elevation. The desired laying is obtained by moving the gun in elevation until the two pointers are matched. The method of laying in elevation by matching pointers has been found to increase the rapidity of laying, particularly for guns which have to be depressed for loading at each round.

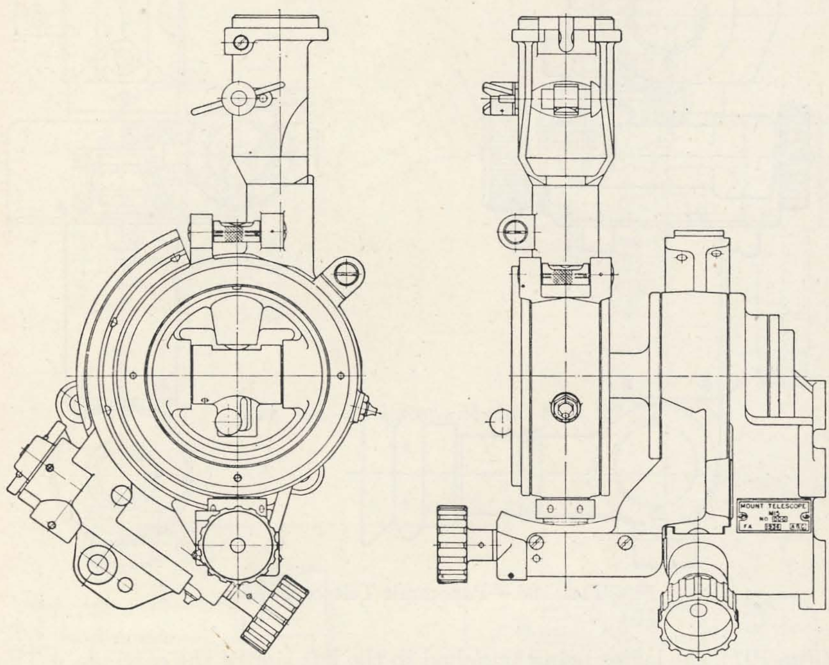


FIG. 197.—Telescope Mount, M15.

269. Sighting Equipment for Medium and Heavy Field Artillery.—The sighting equipment for the 155-mm. Howitzer Carriage, M1918A1, the 155-mm. Gun Carriage, M1918A1, and the 240-mm. Howitzer Carriage, M1918, consists of the Panoramic Telescope, M6, and the Quadrant Sight, M1918A1.

The Panoramic Telescope, M6, is identical with the Panoramic Telescope, M5 (Fig. 196), except for a difference in the method of attaching the telescope to the mount.

The Quadrant Sight, M1918A1, shown in Fig. 199, is attached to the left trunnion, and the panoramic telescope is mounted on the sight shank (1). By means of gearing, operation of the knob (2) causes the gear segment, to which the sight shank is attached, to rotate; and it causes

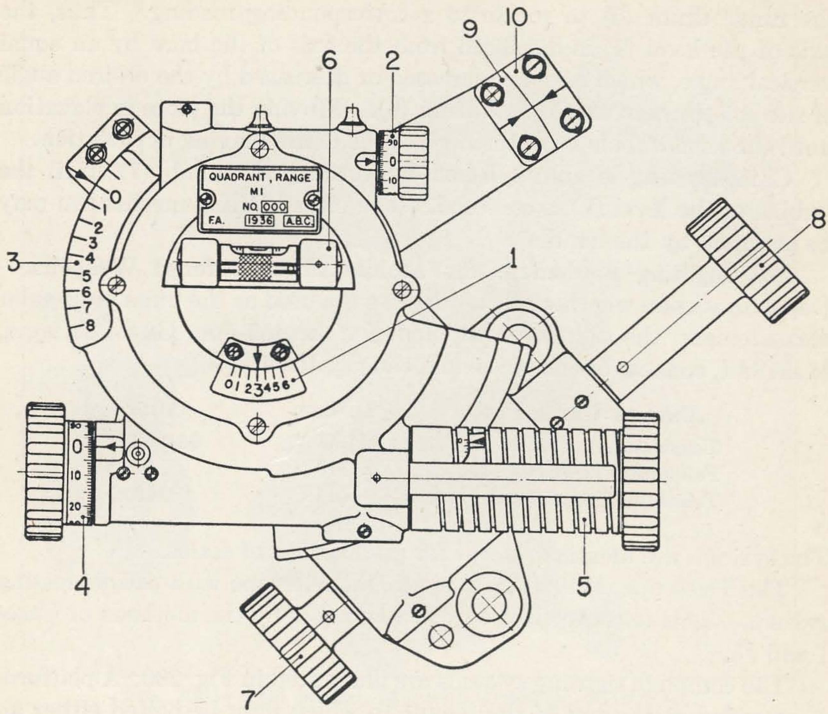


FIG. 198.—Range Quadrant, M1.

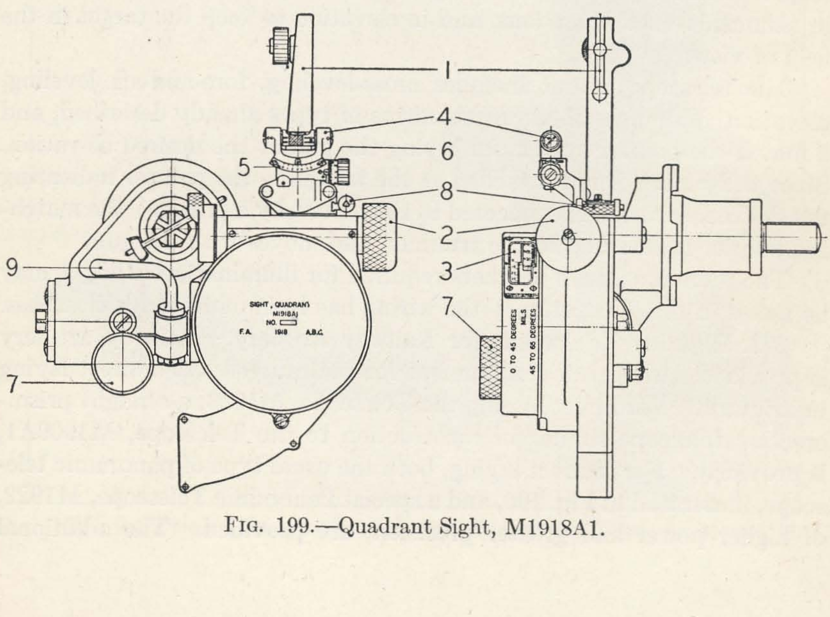


FIG. 199.—Quadrant Sight, M1918A1.

the range drum (3) to rotate to a corresponding reading. Thus, the axis of the level (4) is displaced from the axis of the bore by an equal vertical angle, which may be increased or decreased by the desired angle of site set on the scale (5) and drum (6). Moving the piece in elevation until the level bubble is centered gives the desired laying in elevation.

Cross-leveling is accomplished by turning the knob (7) until the bubble of the level (8) is centered. The cross-leveling mechanism may be clamped by the handle (9).

270. Sighting Equipment for Mobile Coast Defense Weapons.—Depending upon whether mils or degrees are used as the units of angular measurement, the sighting equipment for the 155-mm. Gun Carriages, M1918A1, consists of one of the following systems:

Unit of Graduation	Degree	Mil
Telescope	M1909A1	M1909A1
Panoramic Telescope	M3	M4
Telescope Mount	M4	M6

The systems are identical except for graduations of scales.

The Telescope, M1909A1, is a straight telescope with prism erecting system. This telescope is used when laying is by the methods of Cases I and II.

The complete sighting systems are illustrated in Fig. 200. A platform is provided at the top of the mount to which may be bolted either an adapter for the straight telescope or an adapter for the panoramic telescope. The adapter for the straight telescope provides limited motions in azimuth to set deflections, and in elevation to keep the target in the field of view.

The telescope mount includes cross-leveling, fore-and-aft leveling, elevation, and angle-of-site mechanisms of types already described, and a match-the-pointer system for laying the gun at the desired elevation. Since this mount is not attached at the trunnion, the pointer indicating the desired elevation is connected to the mount by a linkage; the matching pointer is attached to the trunnion and moves with the gun.

The numerous lamp brackets required for illumination at night may be noted in the illustrations; the wiring has been omitted for clearness.

271. Sighting Equipment for Railway Artillery.—Railway artillery is provided with sighting equipment for both direct and indirect laying in azimuth. For direct laying, the Telescope, M1923, a straight prism-erecting telescope similar in construction to the Telescope, M1909A1, is provided. For indirect laying, both the usual type of panoramic telescope, illustrated in Fig. 196, and a special Panoramic Telescope, M1922, of higher power and greater precision, are provided. The additional

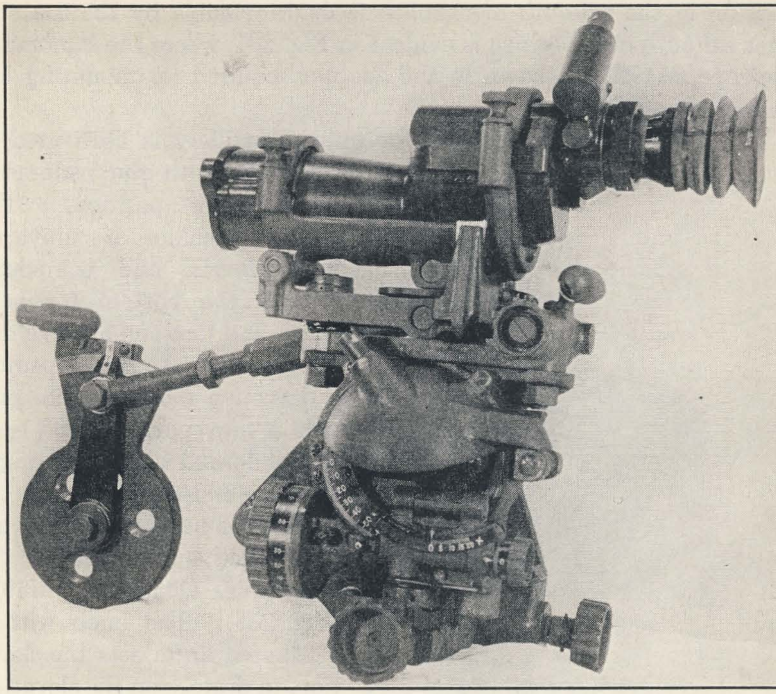


FIG. 200.—Sight Mount, M4, with Telescope, M1909A1.

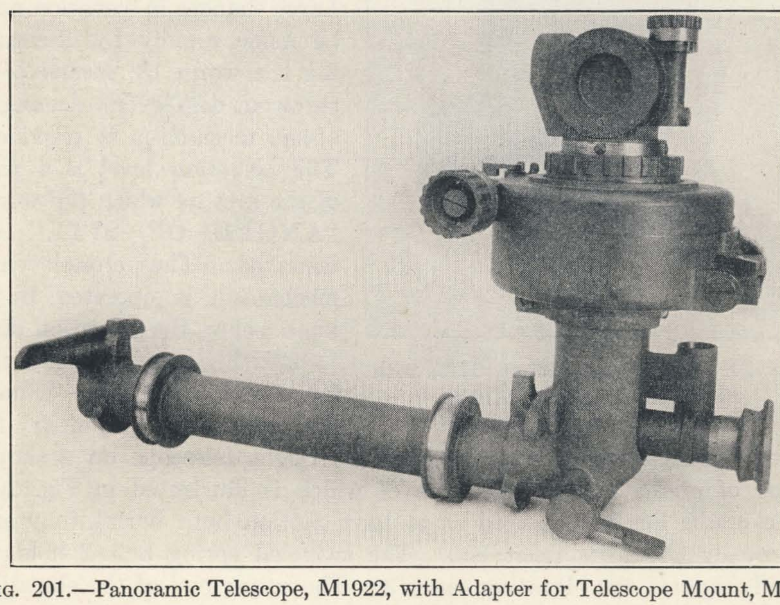


FIG. 201.—Panoramic Telescope, M1922, with Adapter for Telescope Mount, M13.

precision in the azimuth mechanism is made possible by the use of a larger azimuth circle, which is evident in Fig. 201, where the Panoramic Telescope, M1922, is shown in the adapter required for mounting the telescope.

The Telescope Mount, M13, for railway artillery is illustrated in Fig. 202, with the panoramic telescope in position. The mount includes a universal joint, levels, and compound slide at the bottom for both cross- and fore-and-aft leveling. The knob at the right operates a deflection mechanism to provide a movement of 10° each side of normal when the straight telescope is used.

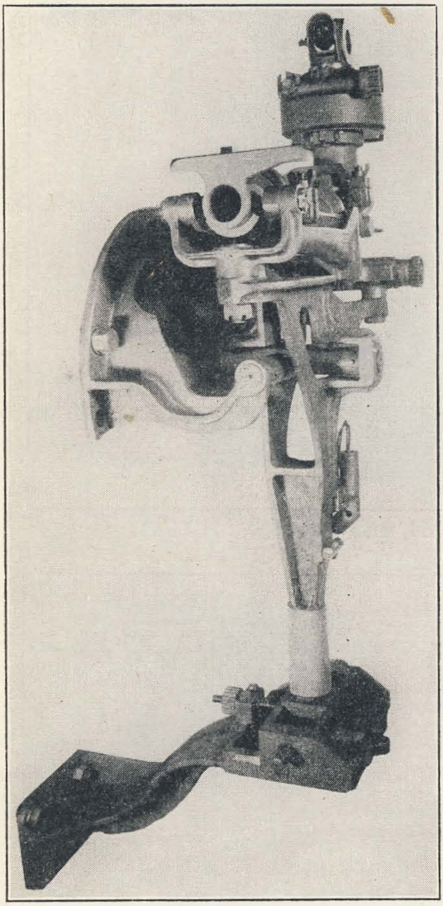


FIG. 202. — Telescope Mount, M13, with Panoramic Telescope, M1922.

Laying in elevation is accomplished by the use of the Elevation Quadrant, M1917 (Fig. 203). The knob with a graduated drum sets the elevation, in degrees on the elevation disc and minutes on the drum. Large changes in elevation may be made rapidly by disengaging the worm by means of a throwout cam lever. An angle-of-site mechanism is provided. The elevation level is a part of the arm on which the words "ANGLE OF SITE" are inscribed. The cross-leveling mechanism is operated by a knob below the elevation disc.

272. Sighting Equipment for Fixed Carriages.—Direct-fire sighting equipment for fixed seacoast weapons consists of a straight telescope on a simple type of cradle mount, one type of which is illustrated in Fig. 204. The cradle 1 is so mounted as to have motion both horizontally and vertically about its front end. The swiveled spring bolt 2 holds it firmly against the elevating screw 3. The upper end of the elevation

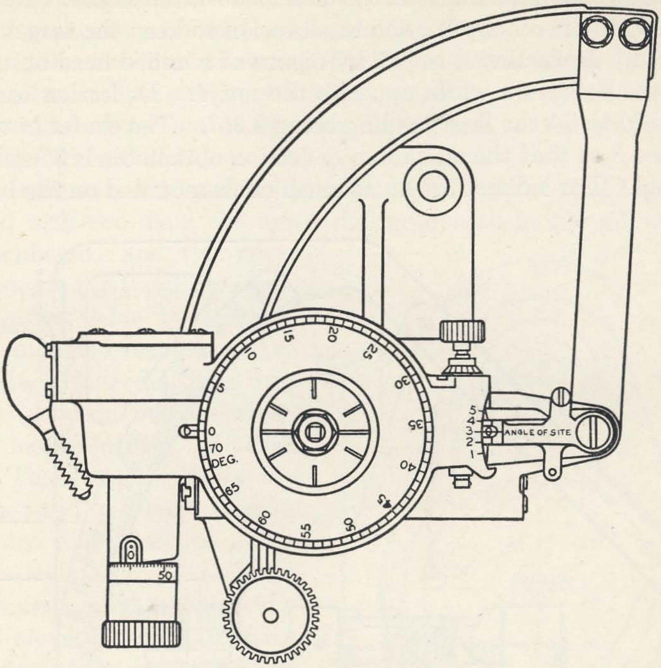


FIG. 203.—Elevation Quadrant, M1917.

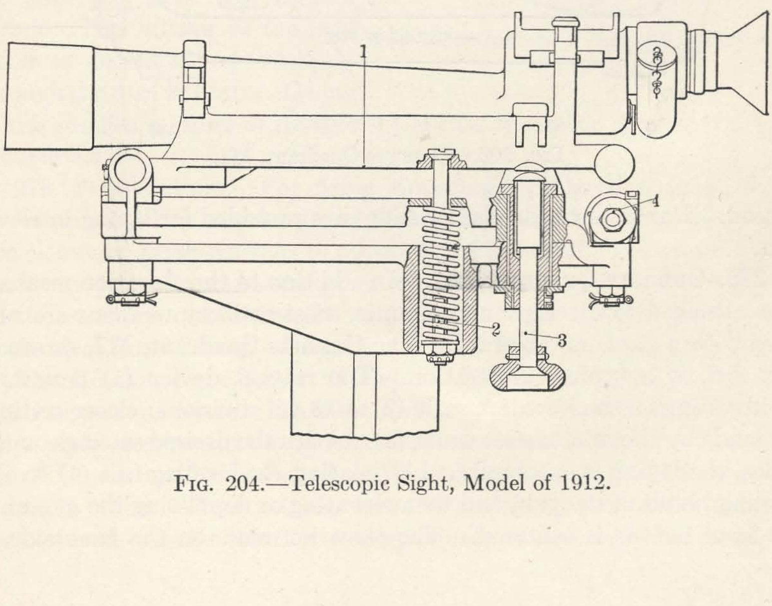


FIG. 204.—Telescopic Sight, Model of 1912.

screw bears on a flat surface on the under side of the cradle. By turning the screw, the necessary motion in elevation to keep the target in view is secured. Deflection is set off by means of a milled head on the right end of the deflection worm opposite the nut 4. Deflection can be set off from 0° to 6°, the least reading being 0.05°. The center of the scale is marked 3 so that the maximum deflection obtainable is 3° either side of normal. For indirect fire an azimuth circle mounted on the base ring

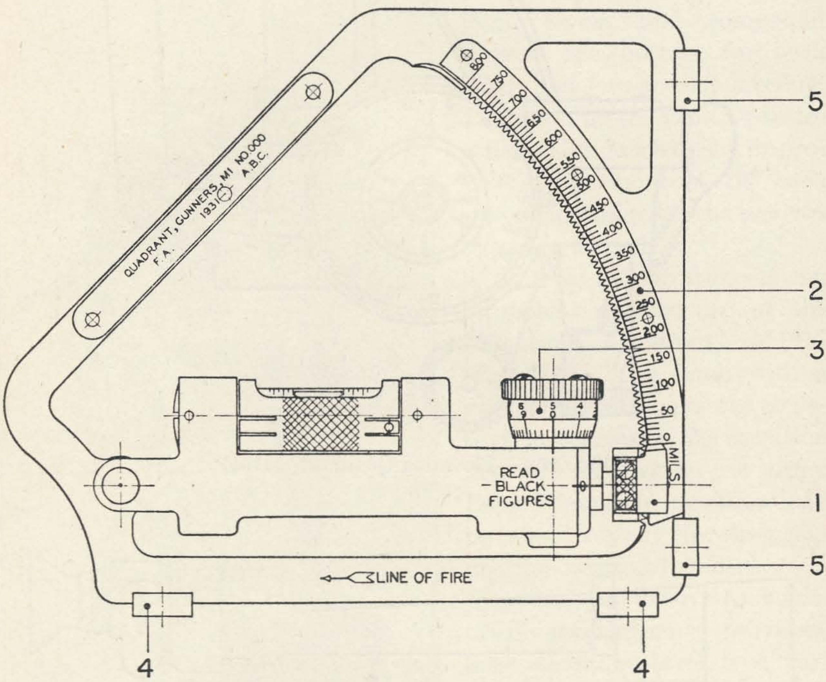


FIG. 205.—Gunners Quadrant, M1.

is used. Range discs, drums, or slides are provided for laying in elevation.

273. Gunners Quadrant, M1.—In addition to the elevation mechanisms attached to carriages and mounts, most artillery weapons are supplied with a gunners quadrant. The Gunners Quadrant, M1, shown in Fig. 205, is a typical illustration. The ratchet device (1) permits a rapid setting on the elevation scale (2) at 10 mil divisions; closer settings are made by the micrometer drum (3). With the desired settings on the scales, the laying is accomplished by placing the leveling feet (4) on the leveling plates of the gun, and then elevating or depressing the gun until the level bubble is centered. The elevation scale on the back side of

the quadrant is graduated from 800 to 1600 mils, and this scale is used when the quadrant rests on the leveling feet (5).

274. Indicators for Antiaircraft Carriages.—The laying in azimuth and elevation and the setting of the fuze setters for antiaircraft carriages are accomplished by means of three indicators, as follows: azimuth, elevation, and fuze.

The Indicator, Azimuth or Elevation, M4, illustrated in Fig. 206, is provided with two dials, the upper dial graduated in 400 mil divisions (not numbered) and the lower dial graduated in 2 mil divisions. The angular value is indicated by the combined readings of the two dials. Each dial has two pointers on annular discs which move independently of each other. The inner pointers are positioned to the desired angular values by the electrical data transmission system. The outer pointers are geared mechanically to the elevating or traversing mechanism of the carriage. Elevation and traverse of the gun until the pointers of the indicators are matched give the desired laying. The setting of the fuze setter is accomplished similarly through the fuze indicator. Owing to the smaller number of divisions, the fuze indicator is equipped with a single dial.

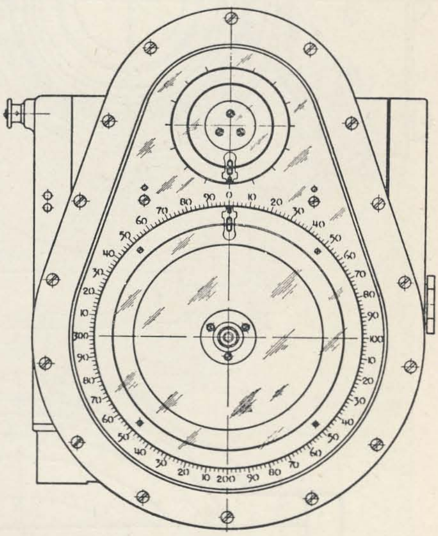


FIG. 206.—Indicator, Azimuth or Elevation, M4.

275. Fuze Setters.—For firing time-fuzed projectiles, fuze setters are required. For powder train fuzes, the desired settings consist of two elements, range settings to adjust times of burning to normal values for the trajectories and settings on an arbitrary *corrector* scale to move the burst in or out along the trajectory to the desired point. For mechanical fuzes, direct settings of times of flight in seconds are made.

The Bracket Fuze Setter, Model of 1916, is illustrated in Fig. 207. The range is set by turning the crank until the desired setting on the range scale is opposite the index. The corrector is set by turning the knurled knob until the desired setting on the correct scale is opposite the same index. These settings serve to position a stop and a notch in the setter in angular relation corresponding to the desired setting. A

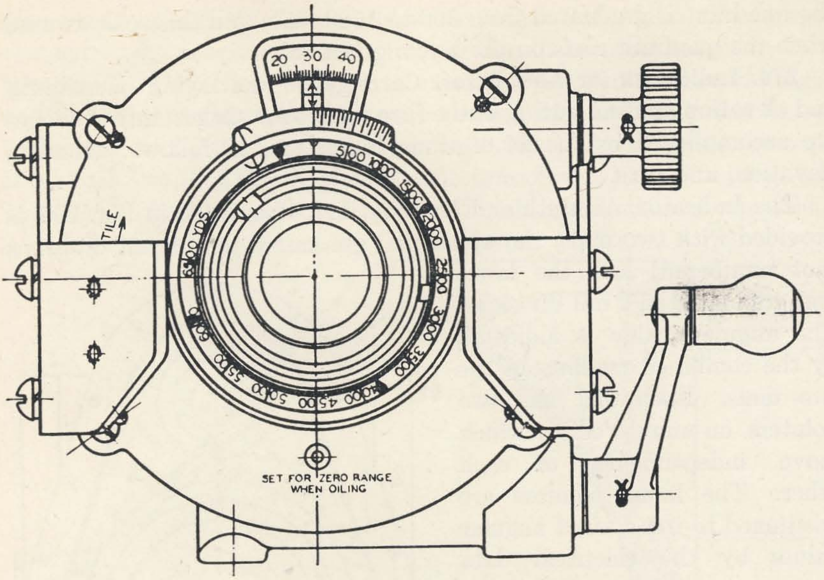


FIG. 207.—Bracket Fuze Setter, Model of 1916.

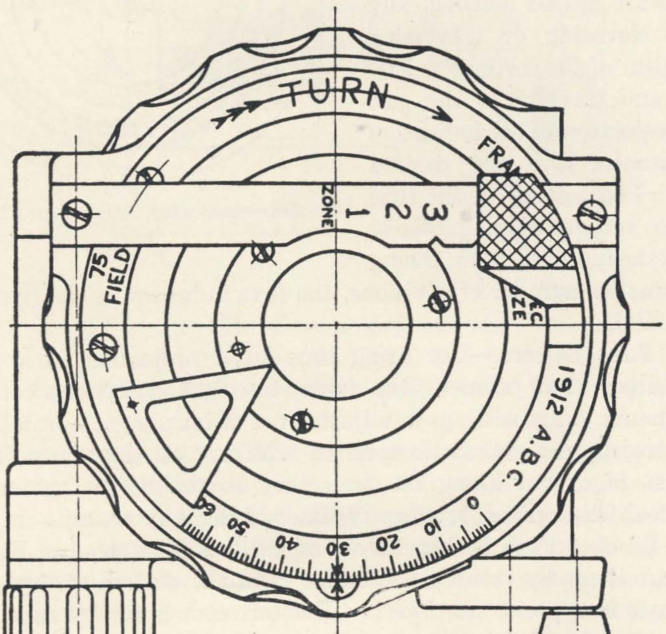


FIG. 208.—Hand Fuze Setter, Model of 1912.

projectile is then inserted into the setter, with the rotating pin of the fuze time-train ring in the notch, and rotated until a lug on the fuze strikes the stop in the setter, thus rotating the fuze time-train ring to the desired setting.

The Hand Fuze Setter, Model of 1912, the top view of which is shown in Fig. 208, operates on the same principle as the bracket fuze setter. In this case the fuze setter is rotated instead of the projectile

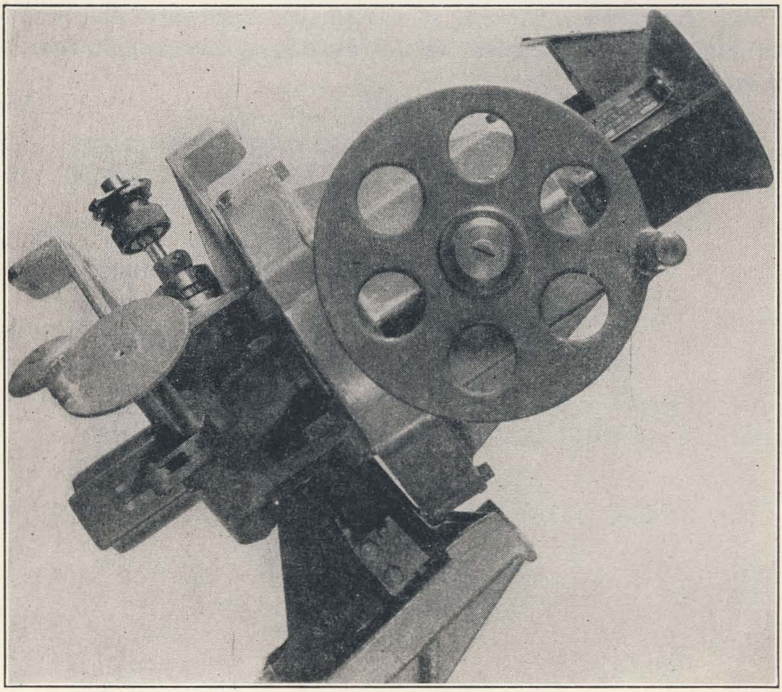


FIG. 209.—Fuze Setter, M6.

for setting a fuze. Each of the three concentric range rings may be graduated so that the movable range pointer with a knurled thumb-piece may be moved to different positions on the cross arm to permit the setter to be used for three zones of fire. When the fuze has been set, the triangular pointer will be opposite a line on the closing cap of the fuze which projects through the circular opening in the center.

Fuze setters can be adapted to different types of ammunition by changing of range rings.

Antiaircraft fuze setters are designed to set time fuzes and keep them set continuously in accordance with data received until the projectiles

are withdrawn from the setter. The 3-in. Antiaircraft Fuze Setter, M6, is illustrated in Fig. 209. Brackets for mounting a fuze indicator, and the coupling for connecting the indicator with the fuze setter, are shown. Turning of the smaller solid handwheel until the pointers of the indicator are matched gives the desired setting to the fuze setter. When a round is inserted in the setter through the bell-mouthed opening, it is automatically locked in the setter and the larger setting handwheel is released. Turning the setting handwheel until it is stopped sets the fuze and unlocks the round. Turning of the smaller handwheel will produce, continuously, changes in fuze setting so long as the round remains in the setter.

CHAPTER X

EXTERIOR BALLISTICS

LIST OF SYMBOLS USED IN THIS CHAPTER AND THEIR MEANINGS.

SYMBOL	MEANING
A	Axial moment of inertia of the projectile.
B	Moment of inertia of the projectile about a transverse axis through its center of gravity.
C	Ballistic coefficient $= \dfrac{m}{id^2}$.
C_L	Drift coefficient $= \dfrac{n}{2\pi\rho gj}$.
D	Drag, or component of the total air resistance acting in a direction opposite to the direction of motion of the projectile with respect to the air.
E_x, E_y, E_z	Symbols for the right-hand sides of Eqs. (14), Section 287; thus $E_x = \dfrac{-\rho \cdot F(u) \cdot u_x}{C}$.
F	Drag function $= K_D \cdot u$.
G	Projectile type.
J	Projectile type.
K_D	Drag coefficient $= \dfrac{D}{\rho d^2 u^2}$.
K_L	Cross wind force coefficient $= \dfrac{L}{\rho d^2 u^2 \sin\delta}$.
K_M	Moment coefficient $= \dfrac{M}{\rho d^3 u^2 \sin\delta}$.
L	Cross wind force or component of the total air resistance R perpendicular to the direction of motion of the projectile acting on the plane of yaw.
M	Moment of overturning force.

Symbol	Meaning
N	The spin of the projectile.
N_R	Component of the total air resistance R perpendicular to the axis of the projectile acting in the plane of yaw.
O	Origin of trajectory and coordinate axes. Also center of gravity of projectile.
P	Center of pressure. Intersection of R and the axis of the projectile.
P_x, P_y, P_z	Components of total force acting on the projectile along the axes, X, Y, Z.
Q	Drift function, $\dfrac{K_L}{K_M \cdot u^2}$.
R	Total or resultant air resistance.
S	The summit of the trajectory.
T	Period of the yaw. Also the temperature of the air.
T_0	The standard air temperature on the absolute Fahrenheit scale.
W	Weight of the projectile.
X	Direction of axis of x.
Y	Direction of axis of y.
Z	Direction of axis of z.
a	Velocity of sound in air.
a_0	Standard velocity of sound in air.
d	Diameter of the projectile. For a gun, the nominal diameter of the bore.
g	Acceleration due to the attraction of gravity.
h	Factor in density law, $\rho = \rho_0 e^{-hy}$. Also the differential interval in numerical integration.
i	Form factor.
j	Drift factor.
m	Mass of the projectile in pounds. Also mass of top.
n	Twist of rifling in calibers per turn.
p	Moment of inertia factor ($A = mpd^2$). Also the barometric pressure.
q	Range wind weighting factor.
s	Stability factor.
t	Time at which projectile reaches the point (x, y, z).
t_ω	Time of flight (to point of fall).
u	Velocity of the projectile with reference to the air.
u_x, u_y, u_z	x, y, and z components of u.

Symbol	Meaning
v	Velocity of the projectile with respect to the ground coordinate system at any time t.
v_0	Initial velocity, the value of v at the origin of the trajectory.
v_ω	Velocity at the point of fall.
v_x, v_y, v_z	x, y, and z components of v.
w	Velocity of the wind.
w_x, w_y, w_z	x, y, and z components of w.
w_p	The pseudo-velocity.
x, y, z	Coordinates of the center of gravity of the projectile at time, t.
x_0, y_0, z_0	Coordinates of the origin of the trajectory, i.e., at $t = 0$.
x_ω	Horizontal range.
y_ω	Altitude of point of fall (in bombing from aircraft, the negative of the altitude to point of release).
z_ω	Deflection (distance).
α	Magnitude of the first maximum yaw. Also azimuth.
β	The range angle (in bombing from aircraft).
δ	Angle between the direction of motion and the axis of the projectile, i.e., the angle of yaw.
ϵ	Angle of site.
ζ	Yaw in the gun.
θ	Angle of inclination of trajectory to horizontal at time, t.
θ_0	Quadrant angle of departure, i.e., initial angle of inclination of trajectory.
θ_a	Angle of inclination of trajectory with respect to axes moving with the air.
θ_a'	Rate of turning of trajectory about a horizontal axis, $\frac{d\theta_a}{dt}$ (air coordinates).
λ	Cross wind force factor $= \frac{L}{\sin \delta}$.
μ	Moment factor $= \frac{M}{\sin \delta}$.

Symbol	Meaning
ρ	Density of the air (lb/ft^3).
ρ_0	Standard density, on the ground.
σ	Viscosity of the air.
ϕ	Angle of orientation of the plane of the yaw.
Ψ	Angular velocity of rotation of the earth.
ω	Angle of fall.
Ω	Point of fall or burst, i.e., the end of the trajectory.

EXTERIOR BALLISTICS

Exterior ballistics is a branch of physics which deals with the motion of projectiles through the air and their behavior during flight. A complete and detailed treatment of this subject is beyond the scope of this book. This chapter will attempt only to state the theoretical principles, describe in a general way the behavior of projectiles during flight, and discuss briefly methods of determining the data which are given in the tables used in the conduct of fire. The term projectile is used in a broad sense to designate any rigid body which is projected or thrown at a target. It includes such missiles as rifle bullets, artillery projectiles, airplane bombs, etc.

276. The Trajectory.—The trajectory is the curve in space traced by the center of gravity of a projectile in its flight through the air. The *origin* of a trajectory is the position of the center of gravity of the projectile at the instant it is released by the projecting mechanism; the position of its center of gravity when the projectile bursts or encounters a medium other than air marks its *end.* The tangent to the trajectory at its origin is the *line of departure*; the angle this line makes with the horizontal is the *quadrant angle of departure.* The vertical plane including the line of departure is the *plane of departure.* In it lie the X (horizontal) and Y (vertical) axes of the coordinate system used in the computation of trajectories, whereas the Z axis lies in a horizontal plane and is perpendicular to the plane of departure.

To describe a trajectory completely it is sufficient to specify the x, y, and z coordinates of the center of gravity of the projectile at any time t after the release by the projecting mechanism; in other words, a trajectory is regarded as defined by

$$x = x(t)$$
$$y = y(t)$$
$$z = z(t)$$

where $x(t)$, $y(t)$, and $z(t)$ are functions of the time t which are equal to zero when $t = 0$.

The trajectory is determined by (*a*) the position of the origin, (*b*) the conditions of projection, (*c*) the ballistic characteristics of the projectile, and (*d*) the characteristics of the air through which it passes.

Projections on the plane of departure of several examples of typical trajectories are shown in Fig. 210.

Here *A* and *B* illustrate trajectories of projectiles fired from field artillery weapons at ground targets, the first with a high initial velocity and a low quadrant angle of departure, and the second with a lower initial velocity and a high angle of departure. In antiaircraft fire the trajectories are, in general, as shown in *C*; whereas the one shown in *D* is typical of those described by bombs in horizontal flight bombing.

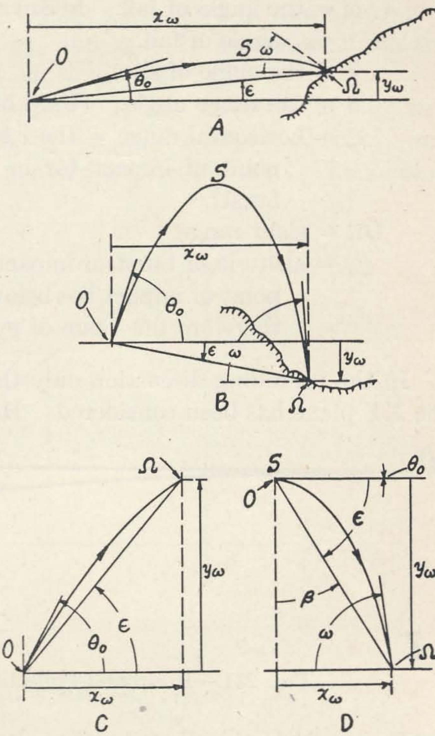


FIG. 210.—Typical Trajectories.

The following symbols indicate certain important characteristic points or dimensions of the trajectories which may be referred to as the elements of the trajectory.

O = the origin.

Ω = the point of impact,
the point of burst (in antiaircraft fire).

S = the summit. In antiaircraft fire, the projectile usually bursts before the summit is reached. In horizontal flight bombing, the summit is also the origin of the trajectory.

OS = the ascending branch. In antiaircraft fire, the whole of the trajectory is generally in the ascending branch. In horizontal flight bombing, there is no ascending branch.

$S\Omega$ = the descending branch. In antiaircraft fire, the descending branch is generally missing. In horizontal flight bombing, only the descending branch is used.

θ_0 = the quadrant angle of departure. In horizontal flight bombing, the quadrant angle of departure is zero.

ω = the angle of fall. In antiaircraft fire, the trajectory has no angle of fall.

ϵ = the angle of site.

β = the range angle. (Used only in bombing from aircraft.)

x_ω = horizontal range = the x coordinate of the trajectory at the point of impact (or in antiaircraft fire at the point of burst).

$O\Omega$ = slant range.

y_ω = altitude of burst or impact. In bombing from aircraft, the point of impact lies below the origin of the trajectory and therefore the value of y_ω is negative.

In the preceding discussion only the projection of the trajectory on the XY plane has been considered. However, the usual trajectory does

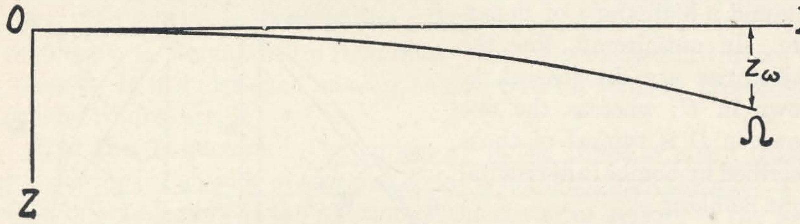


FIG. 211.—Horizontal Projection of Typical Trajectory.

not lie wholly in this plane but has also a projection on the XZ plane as shown in Fig. 211. The deflection shown is exaggerated. The z coordinate of the point of fall is designated by z_ω and is called the *deflection.* The component or part of the deflection not due to the wind is called *drift.*

277. The Principal Problem of Exterior Ballistics and the General Method of Solution.—The principal problem of exterior ballistics is the calculation of the trajectory of a projectile of given characteristics, launched with a given velocity, at a given angle of projection or quadrant angle of departure.

To make the problem more definite it is stated in mathematical terms. A system of rectangular coordinates is chosen as described in Section 276 and shown in Fig. 212.

The initial velocity of the projectile is v_0 and the tangent to the trajectory at the origin makes an angle, θ_0, with the X axis. This angle is called the angle of projection or the quadrant angle of departure.

The coordinates of the center of gravity of the projectile at any time

t are designated by x, y, and z, and the initial values at the time $t = 0$ by x_0, y_0, and z_0. The components of the projectile velocity in the corresponding directions are designated by v_x, v_y, and v_z, and the initial values at the time $t = 0$ by v_{x_0}, v_{y_0}, and v_{z_0}. It is evident from the figure that $v_{x_0} = v_0 \cos \theta_0$, $v_{y_0} = v_0 \sin \theta_0$, $v_{z_0} = 0$.

The problem may now be restated. If the projectile is launched with $x_0 = y_0 = z_0 = 0$, and with $v_{x_0} = v_0 \cos \theta_0$, $v_{y_0} = v_0 \sin \theta_0$ and $v_{z_0} = 0$, it is desired to compute x, y, and z as functions of t. The method

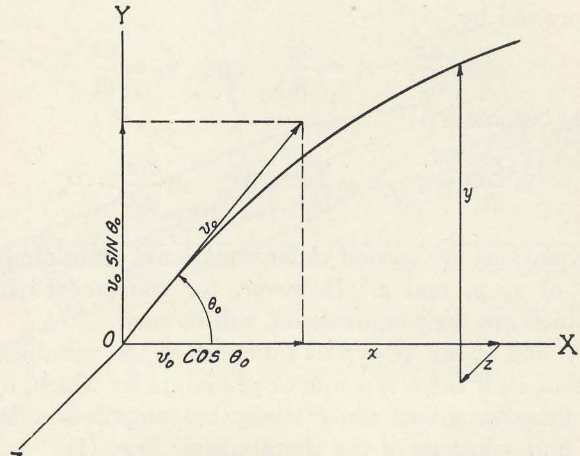


FIG. 212.—Coordinate System and Trajectory.

by which this problem is solved is based on Newton's second law of motion:

$$\textit{Mass} \times \textit{acceleration} = \textit{force}.$$

This is a vector equation; that is, not only is the product of the mass and acceleration equal to the force in magnitude, but also the directions of the force and the acceleration are identical.

For the purpose of computation, the components of the acceleration and of the force are taken along each of the three coordinate axes. For each axis,

$$\textit{Mass} \times \textit{component of acceleration} = \textit{component of force}.$$

For the three axes X, Y, and Z, the components of the acceleration are

$$\frac{dv_x}{dt}, \quad \frac{dv_y}{dt}, \quad \text{and} \quad \frac{dv_z}{dt},$$

and the components of the force are P_x, P_y, and P_z.

If m is the mass of the projectile,

$$m \frac{dv_x}{dt} = P_x, \quad m \frac{dv_y}{dt} = P_y, \quad m \frac{dv_z}{dt} = P_z. \tag{1}$$

These equations are based on the assumption that the coordinate system is attached to a motionless earth. For the present, the small error due to the rotation of the earth will be disregarded.

From the definition of velocity, the velocity components, v_x, v_y, v_z, may be expressed by

$$v_x = \frac{dx}{dt}, \quad v_y = \frac{dy}{dt}, \quad \text{and} \quad v_z = \frac{dz}{dt}$$

and Eqs. (1) become

$$m \frac{d^2x}{dt^2} = P_x, \quad m \frac{d^2y}{dt^2} = P_y, \quad m \frac{d^2z}{dt^2} = P_z.$$

These equations are second order equations, containing the second derivatives of x, y, and z. However, for convenience in notation, Eqs. (1), which are their equivalents, will be used.

If P_x, P_y, and P_z are known as functions of the variables, x, y, z, v_x, v_y, and v_z, that is, if there is a rule or procedure by which, if the values of the variables are given, the P's may be computed, it is in general possible to find solutions of the simultaneous Eqs. (1).

If solutions are obtained which are consistent with the initial conditions, $x_0 = y_0 = z_0 = 0$, $v_{x_0} = v_0 \cos \theta_0$, $v_{y_0} = v_0 \sin \theta_0$ and $v_{z_0} = 0$, then they are solutions of the stated problem. It could also be shown that the solutions are unique, that is, that no other solutions of the equations are solutions of the stated problem.

278. The Forces Acting on the Projectile.—Consider a projectile moving in still air as shown in Fig. 213 with its axis making an angle δ with the direction of motion. It will be acted on by gravity W, acting vertically downward, and an air force R, which will depend upon the velocity, the characteristics of the air and of the projectile, and upon the presentation of the projectile with respect to the direction of motion.

If δ were zero and the projectile symmetrical about its axis, R would point in a direction opposite to the direction of motion. In general, δ is not zero and thus R intersects the direction of motion. The calculations are simplified by considering R as equivalent to two components, one having a direction opposed to the motion, called the drag or head resistance, and designated by D. The other is perpendicular to the direction of motion; it is called the cross wind force, and is designated by L.

It will be pointed out later that the magnitudes of D and L, which

depend upon the air speed, the characteristics of the projectile and the air, and of the angle of yaw δ, may be expressed in terms of the variables v_x, v_y, v_z, x, y, and z.

To determine the force components P_x, P_y, and P_z, it is necessary to know not only the magnitudes of D and L but also their components along the three axes, X, Y, and Z. Hence, both the directions and mag-

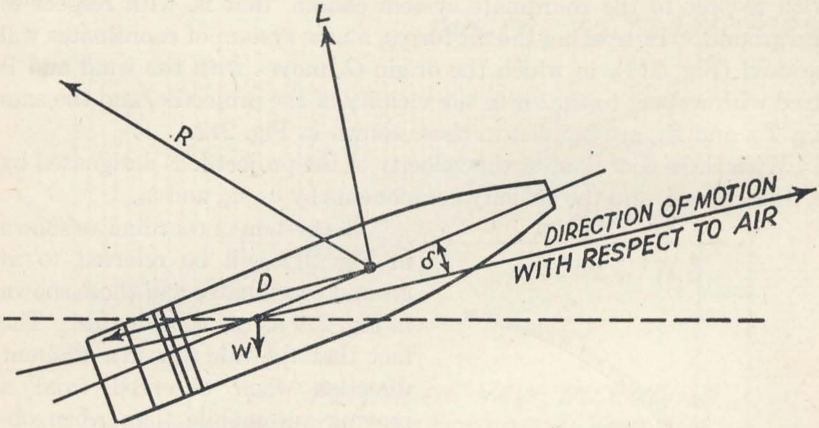


FIG. 213.—Forces Acting on the Projectile.

nitudes of D and L must be known, as depending upon v_x, v_y, v_z, x, y, and z.

The components of D are designated D_x, D_y, and D_z; and those of L by L_x, L_y, and L_z. If the absolute magnitude of W is designated by mg, the components of W are 0, $-\ mg$, and 0. With this notation,

$$P_x = -\ D_x \mp L_x$$
$$P_y = -\ D_y + L_y - mg$$
$$P_z = -\ D_z + L_z$$

and the equations of motion (1) may be written as

$$\begin{aligned} m\frac{dv_x}{dt} &= -\ D_x \mp L_x \\ m\frac{dv_y}{dt} &= -\ D_y + L_y - mg \\ m\frac{dv_z}{dt} &= -\ D_z + L_z \end{aligned} \tag{2}$$

For the solution of these equations, D_x, D_y, D_z, L_x, L_y, and L_z must be known as functions of x, y, z, v_x, v_y, and v_z.

279. Gravity.—For any except the longest trajectories, it may be assumed that the force of gravity is independent of the altitude y, and that its line of action has no x and z components, but is parallel to the vertical through the gun.

280. Air Resistance.—The air forces acting on the projectile depend upon its velocity and presentation with respect to the air and not directly with respect to the coordinate system chosen, that is, with respect to the ground. In treating the air forces, a new system of coordinates will be used (Fig. 214), in which the origin O_a moves with the wind and is fixed with respect to the air in the vicinity of the projectile, and the axes X_a, Y_a, and Z_a, are parallel to those shown in Fig. 212.

With these coordinates, the velocity of the projectile is designated by u, its air speed, and the velocity components by u_x, u_y, and u_z.

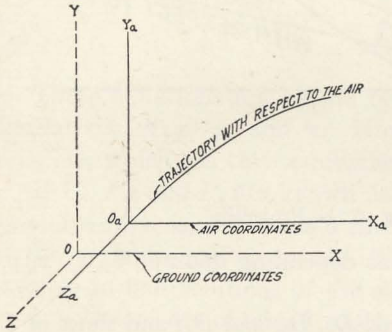


FIG. 214.—Air Coordinate System.

The system of coordinates shown in Fig. 212 will be referred to as ground coordinates and those shown in Fig. 214 as air coordinates. The fact that the rain falls in a different direction when observed from a moving automobile than when observed from the ground explains the necessity of distinguishing between the two coordinate systems.

A projectile is an elongated solid of revolution. As it moves along its trajectory, its axis of symmetry makes an angle δ, called the *angle of yaw*, with the direction of motion, as shown in Fig. 213.

The plane including the axis of the projectile and the tangent to the trajectory makes an angle ϕ, called the *angle of orientation*, with the vertical plane including the tangent to the trajectory as shown in Fig. 215. As observed from the origin of the trajectory, ϕ is measured in a clockwise direction.

The meaning of these terms is made clearer by the photograph (Fig. 216) of a cardboard through which a bullet has been fired with its trajectory perpendicular to the cardboard. The length of the major axis of the hole in the cardboard depends upon the angle of yaw δ, and the angle of orientation ϕ is the angle between the vertical and the major axis of the hole.

Consider now the forces acting upon the projectile as dependent on the characteristics of the projectile, the characteristics of the air, the air speed u and the angles δ and ϕ. If the projectile is at rest with respect

to the air, the pressure on all parts of its surface is uniform, and there are no forces acting tangentially to the surface because the rate of shear of

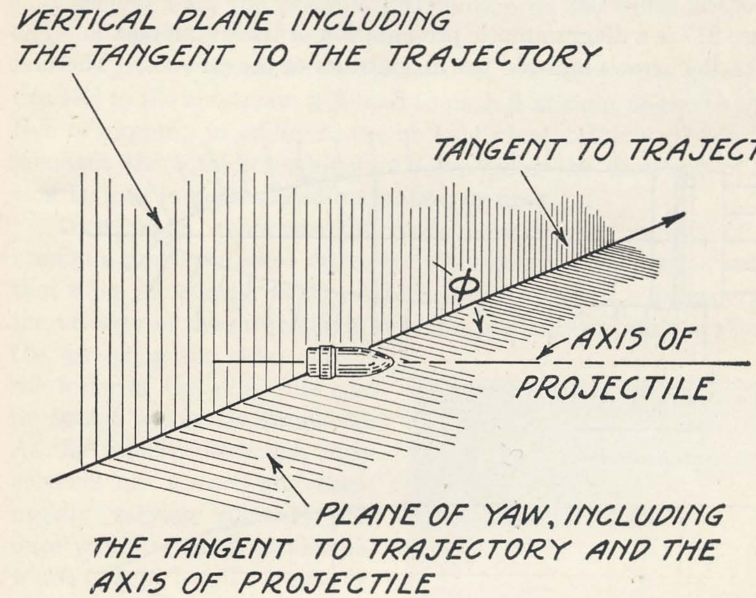


FIG. 215.—Angle of Orientation, ϕ.

the air in its vicinity is zero. By shear in air is meant the relative motion of parallel plane layers of infinitesimal thickness in a direction along their planes.

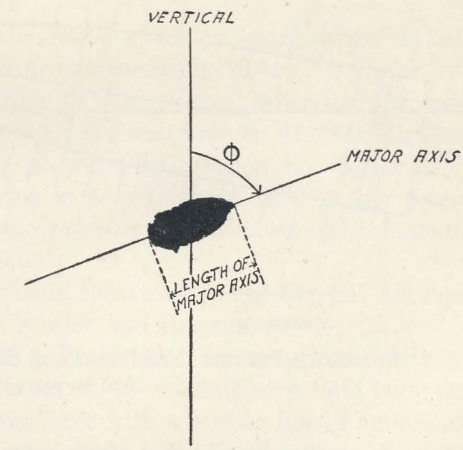


FIG. 216.—Hole in a Cardboard made by a Yawing Projectile.

If a velocity is imparted to the projectile, the pressure on that part towards the direction of motion generally will be greater than the pressure on the part away from the direction of motion. Friction causes the layer of air in contact with the surface to be dragged along with the projectile and to slide past the more distant layers. As a result, tangential shearing forces will also be applied to the surface of the projectile. The preponderance of the pressure

on the part of the surface towards the direction of motion over that away from it, combined with the shearing stresses, will tend to retard the motion of the projectile.

Figure 217 is a diagrammatic presentation of these statements. The lengths of the arrows indicate the magnitudes of the stresses. The first

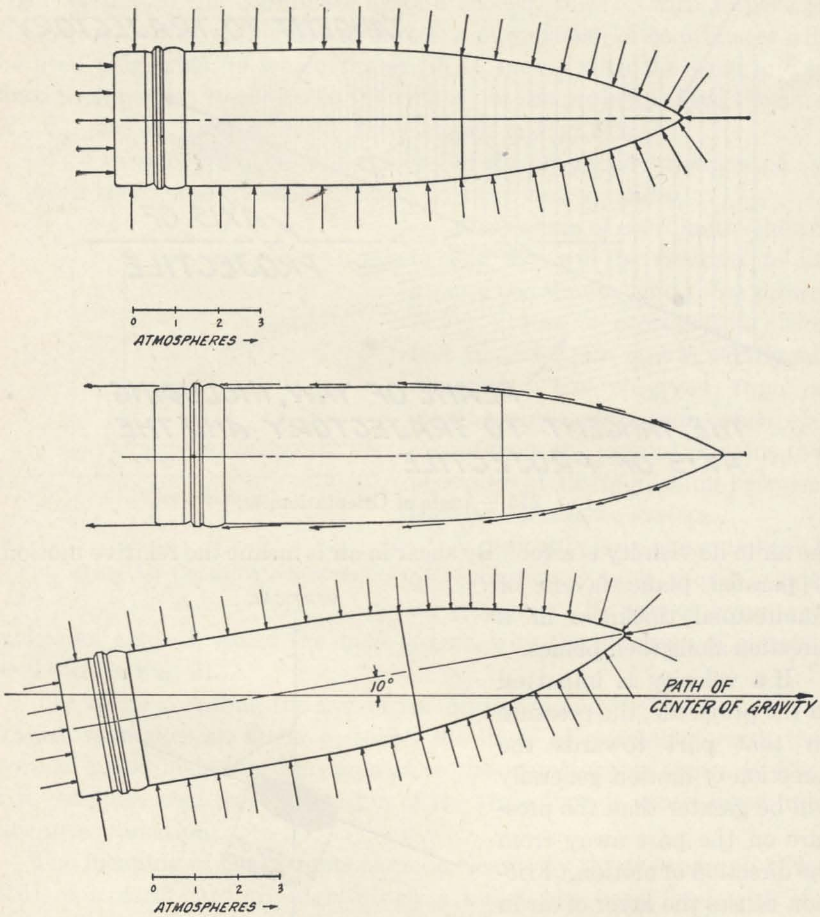


FIG. 217.—Pressure Distribution and Shearing Stresses on a Shell (u = 1000 ft. per second).

sketch shows the distribution of pressure on a 3-in. shell moving with zero yaw at a velocity of about 1000 ft. per second, or about 9/10 that of sound. The middle sketch is an attempt to show the shearing stresses on the same shell. However, nothing is definitely known of the dis-

tribution of the shearing stresses. Hence, the relative magnitudes shown are without experimental basis. The bottom sketch represents, in a general way, the pressure distribution on the same shell, with an angle of yaw of 10° instead of zero.

The greater pressure on the side of the projectile more directly exposed to the air stream will tend to push it at right angles to the direction of motion; in addition, the oblique presentation will considerably augment the total component of force along the direction of motion, that is, yaw increases head resistance, or drag.

There is an important difference between the motion of the air around a projectile when its velocity is below the velocity of sound and that when its velocity is above the velocity of sound. In general, when the velocity of the projectile is very low, no eddy currents are formed in the air along the sides and in the wake of the projectile and no sound waves are produced. As the velocity is raised, eddy currents are formed and these rapidly varying currents produce waves of small amplitude, which may be heard. However, not until the projectile reaches the velocity of sound are the pressure waves of large amplitude formed which move with the projectile and produce the *crack* which is heard when a bullet passes overhead. These waves are shown in Fig. 218.

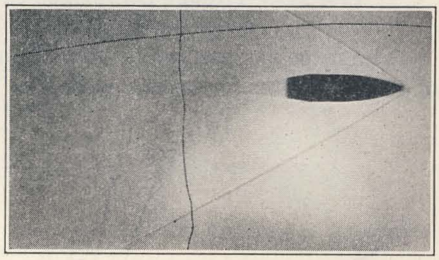


FIG. 218.—Spark Photograph of Bullet Moving at Velocity of about 2600 ft. per second.

As a result of the formation of such waves, when the projectile velocity reaches that of sound, there is a sharp rise in the total air resistance. Figure 219 shows the pressure distribution on the projectile shown in Fig. 217 when moving at a velocity of 1230 ft. per second. The considerable *increase* of the pressure on the nose and the smaller *decrease* on the base will be noted.

Figure 219 and also the first and third sketches of Fig. 217 are based on measurements by Bairstow, Fowler, and Hartree.

281. The Force System of a Projectile.—In accordance with the principles of mechanics, the system of forces acting on a rigid body may be replaced by a single resultant force with a certain line of action, and a couple tending to cause rotation about this line of action. In a projectile this couple is small and will be neglected. The force system, therefore, is replaced by a single force with a definite line of action which, without serious error, may be assumed to pass through the axis of the

projectile. It is also assumed that the line of action is in the plane of yaw.

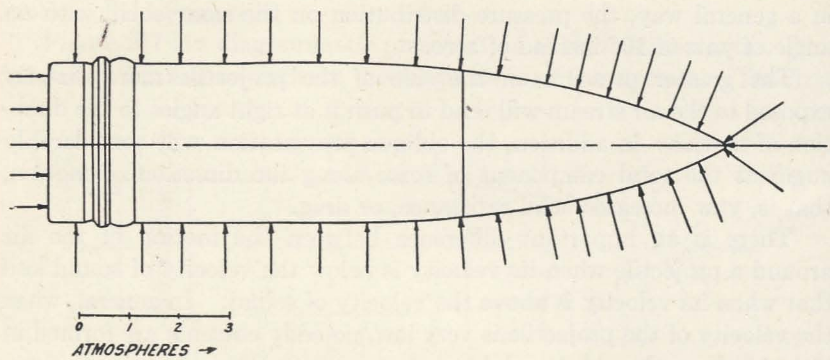


FIG. 219.—Pressure Distribution on Shell (u = 1230 ft. per second).

The force system acting on a 75-mm. projectile moving at a velocity of about 2200 ft. per second with $\delta = 10°$ is shown in Fig. 220.

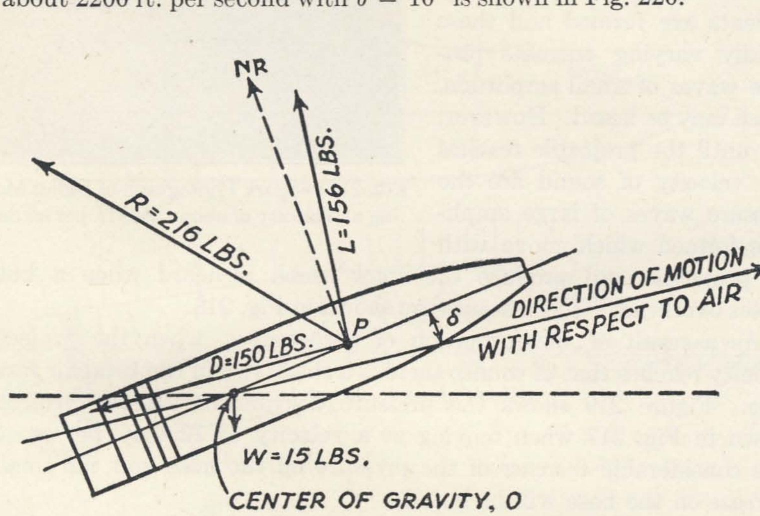


FIG. 220.—Force System of a 75-mm. Projectile (u = 2200 ft. per second).

The forces in the figure are given in pounds. During the remainder of the chapter, however, they will be given in poundals, the poundal being the absolute unit of force in the pound-foot-second system, that is, the force which will impart to a mass of 1 lb. an acceleration of 1 ft. per second per second. The numerical measure of the force in poundals is equal to the force in pounds multiplied by g.

The meanings of the symbols used are given in the following table:

SYMBOL	MEANING	NAME
R	Total or resultant air resistance acting on the projectile	Total resistance
D	The component of R acting in a direction opposite to the direction of motion with respect to the air	Head resistance or drag
L	Component of R acting in the plane of yaw perpendicular to the direction of the motion	Cross wind force
W	Force of gravity	Weight
N_R	Component of R acting in the plane of yaw perpendicular to the axis of the shell *	Normal force
P	Intersection of R and axis of projectile	Center of pressure
O	Position of the center of gravity	Center of gravity
M	Moment exerted by R or N_R about O	Overturning moment
OP	Distance between the center of gravity and the center of pressure	Arm of the normal force
δ	Angle between the direction of the motion and the axis of the shell	Angle of yaw

* R is considered as the resultant of a force N_R perpendicular to the axis and a force not shown acting along the axis. The force not shown has no arm about O.

If a rigid body is acted on by a force R, the acceleration of the center of gravity O is equivalent to that which would be produced if the line of action of R passed through O. In addition there is an angular acceleration equal to that produced by a couple, the moment of which is equal in magnitude and direction to the moment M of R about O. The large overturning moment M is not to be confused with the true couple which, as was stated, is negligible. M is equal to the product of N_R and the distance OP, and is equivalent to a couple tending to overturn the projectile unless, as is the case with airplane bombs and other fin stabilized projectiles, the center of pressure P is nearer the base than O, the center of gravity. A spin is imparted to artillery projectiles by the rifling to prevent the occurrence of large angles of yaw δ except on trajectories with a large quadrant angle of departure.

It is evident that M, N_R, and L disappear with δ. This is shown by letting

$$M = \mu \sin \delta$$

where μ is called the moment factor,

$$L = \lambda \sin \delta$$

where λ is called the cross wind force factor, and

$$N_R = \nu \sin \delta$$

where ν is called the normal force factor.

For small angles of yaw, the factors μ, λ and ν are nearly independent of δ. No reference has been made to a swerving force due to the spin, which acts in a direction perpendicular to the plane of the figure. Its influence on the trajectory of ordinary military projectiles is relatively small and will be disregarded.

282. Force and Moment Coefficients.—For a *given projectile shape*, the air forces acting on a projectile fired into the air are considered to depend upon the parameters given with their symbols in the following table.

Symbol	Meaning	Units
d	diameter of projectile	ft.
ρ	density of air	lb. per ft.^{3}
δ	angle of yaw	degrees or radians
u	velocity relative to the air	ft. per second
a	velocity of sound in air	ft. per second
σ	viscosity of the air*	$\dfrac{\text{lb.}}{\text{ft.} \times \text{sec.}}$

* If two parallel planes are at unit distance apart in a fluid, and one of them is moving in its own plane with unit velocity relatively to the other plane, then the tangential force exerted per unit area on each of the planes is equal to the viscosity.

The drag D and the cross wind force L may now be expressed in terms of the above symbols as follows:

$$D = K_D \rho d^2 u^2 \tag{3}$$

$$L = \lambda \sin \delta = K_L \rho d^2 u^2 \sin \delta \tag{4}$$

In these expressions, K_D and K_L are called the drag and cross wind force coefficients respectively. They are functions of the parameters $\frac{\rho u d}{\sigma}$, $\frac{u}{a}$, and δ. For different shapes of projectile the K's depend upon the parameters in different ways.

The overturning moment M is likewise expressed as follows:

$$M = \mu \sin \delta = K_M \rho d^3 u^2 \sin \delta \tag{5}$$

K_M, called the moment coefficient, is considered to be a function of

$\frac{\rho u d}{\sigma}$, $\frac{u}{a}$, and δ. Its magnitude also depends upon the position of the center of gravity O.*

In the following discussion the dependence of the force coefficients upon u/a and δ will be discussed but their dependence upon $\frac{\rho u d}{\sigma}$ (known as the Reynolds number) will be disregarded since very little is known about it.

Determinations of K_D, K_L, and K_M as functions of u/a have been made for small yaws for several projectile types. Some of the results are given in Figs. 221, 222, and 223. Figure 221 shows K_D plotted as a function of u/a for two different types of artillery projectiles. One was formulated by the French at Gâvre for a projectile with a flat base and a 2-caliber radius of ogive; the other, determined at the Aberdeen Proving Ground, is the drag coefficient for a long-pointed, boat-tailed projectile, type J. Figure 222 shows K_L, the cross wind force coefficient, as a function of u/a for small yaws for two different types of artillery projectiles. One curve was determined by Fowler, Gallop,

* There is experimental evidence that K_D, K_L, and K_M do in fact depend upon $\frac{\rho u d}{\sigma}$, $\frac{u}{a}$, and δ. Furthermore, the assumption that they do is consistent with the requirement that the units on both sides of Eqs. (3) and (4) must be the same.

The units of a force such as D are $\frac{(\text{lb.})(\text{ft.})}{(\text{sec.})^2}$. The units of the expression, $\rho d^2 u^2$, are $\frac{(\text{lb.})}{(\text{ft.})^3}\cdot(\text{ft.})^2\cdot\frac{(\text{ft.})^2}{(\text{sec.})^2} = \frac{(\text{lb.})\cdot(\text{ft.})}{(\text{sec.})^2}$. Thus if the units of the two sides of the equation

$$D = K_D \rho d^2 u^2$$

are to agree, K_D must have no units.

The units of $\frac{\rho u d}{\sigma}$ and $\frac{u}{a}$ are respectively

$$\frac{\frac{(\text{lb.})}{(\text{ft.})^3}\cdot\frac{(\text{ft.})}{(\text{sec.})}\cdot(\text{ft.})}{\frac{(\text{lb.})}{(\text{ft.})\cdot(\text{sec.})}} = 1$$

and

$$\frac{\frac{(\text{ft.})}{(\text{sec.})}}{\frac{(\text{ft.})}{(\text{sec.})}} = 1.$$

δ has no units in (lb.), (ft.), or (sec.). Thus, the requirements that K_D, etc., have no units is satisfied.

Lock, and Richmond for a 3-in. projectile with a flat base and an ogive 1.8 calibers high. The other curve was obtained at the Aberdeen Proving Ground with the type J projectile.*

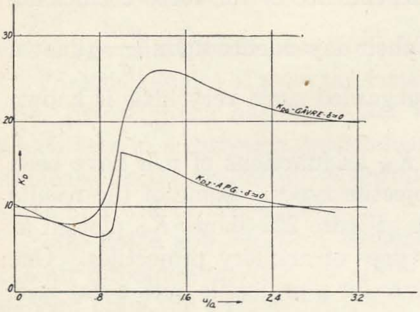


FIG. 221.—K_D for Two Projectile Shapes.

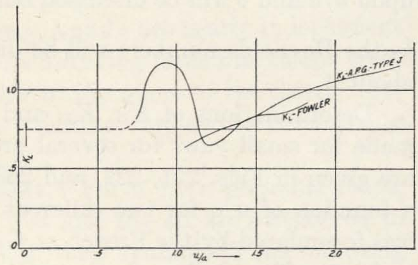


FIG. 222.—K_L for Two Projectile Shapes.

Figure 223 shows values of the moment coefficient K_M as determined for the two projectiles, the K_D's and K_L's of which are shown in Figs. 221 and 222.

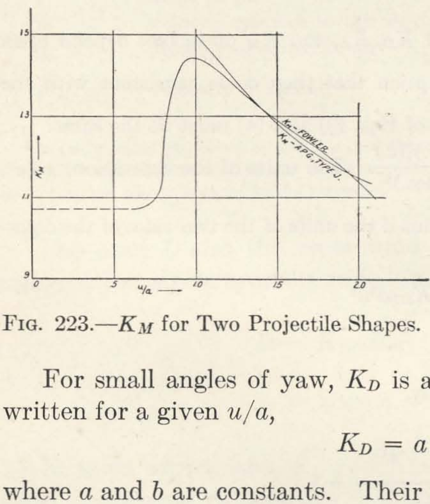


FIG. 223.—K_M for Two Projectile Shapes.

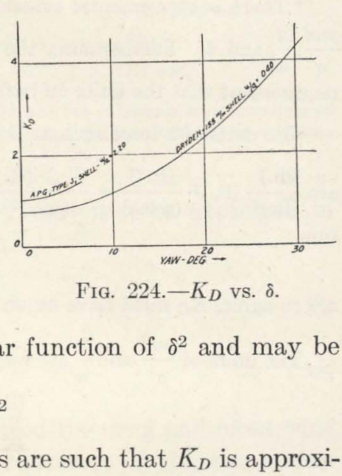


FIG. 224.—K_D vs. δ.

For small angles of yaw, K_D is a linear function of δ^2 and may be written for a given u/a,

$$K_D = a + b\delta^2$$

where a and b are constants. Their values are such that K_D is approximately twice as great for $\delta = 13°$ as it is for $\delta = 0$ for normal projectiles.

Figure 224 is a plot of K_D vs. δ for a 155-mm. projectile, as obtained by H. L. Dryden at the National Bureau of Standards. It also gives approximate results for the type J projectile, obtained by resistance firings at Aberdeen Proving Ground.

* The center of gravity of the projectile fired by the British was 1.58 calibers from the base, whereas that of the projectile fired at the Proving Ground was 1.92 calibers from the base.

For small yaws, K_L and K_M are approximately independent of δ. Figures 225 and 226 show K_L and K_M, respectively, as functions of δ for a 155-mm. projectile as obtained by Dryden.

Although it is not feasible to express the dependence of the K curves on shape by means of definite functional relations, it cannot be too strongly emphasized *that the forms of the K curves as functions of u/a and δ are, in general, different for each shape of projectile.* In addition, K_M depends upon the position of the center of gravity.

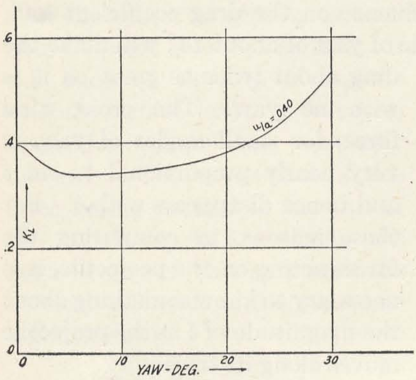


FIG. 225.—K_L vs. δ.

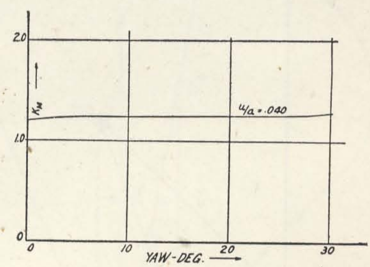


FIG. 226.—K_M vs. δ.

Since the coefficients K, and the forces themselves, depend upon the velocity of sound a, the air density ρ, and the yaw δ, the manner in which the values of a, ρ, and δ may be determined will be discussed.

The velocity of sound is given by the expression $a = a_0 \, (T/T_0)^{1/2}$, where a and a_0 are the velocities of sound in air having the absolute temperatures, T and T_0 respectively.

If a gas has a given composition, the density or the mass per unit volume is given by

$$\rho = \frac{k \cdot p}{T}$$

where k is a constant, p is the barometric pressure, and T is the absolute temperature. Actually the air of the atmosphere is not dry and the density depends to a slight extent upon the humidity. In actual practice, the density is obtained from meteorological tables.

The velocity of the projectile u with respect to the air depends upon its velocity v with respect to the ground, and also upon the velocity of the wind w with respect to the ground. In fact the velocity v is the vector sum or resultant of w and u, whereas u is the vector difference of v and w, as shown in Fig. 227.

If the components of the velocity u are designated by u_x, u_y, and u_z; the components of v by v_x, v_y, and v_z; and of w by w_x, w_y, and w_z;

$$u_x = v_x - w_x, \quad u_y = v_y - w_y, \quad u_z = v_z - w_z.$$

Since u_x, u_y, and u_z are the components of u, it follows that $u^2 = u_x^2 + u_y^2 + u_z^2$.

283. The Yaw of the Projectile, the Stability Factor.—The yaw of the projectile has a considerable influence on the drag coefficient and, hence, on the drag. In fact, an angle of yaw of about 13° will make the drag about twice as great as it is with no yaw. The cross wind force, for small angles of yaw, is very nearly proportional to sin δ and hence disappears with δ. For these reasons, in computing the forces acting on the projectile, it is necessary to know something about the magnitude of δ as the projectile moves along its trajectory.

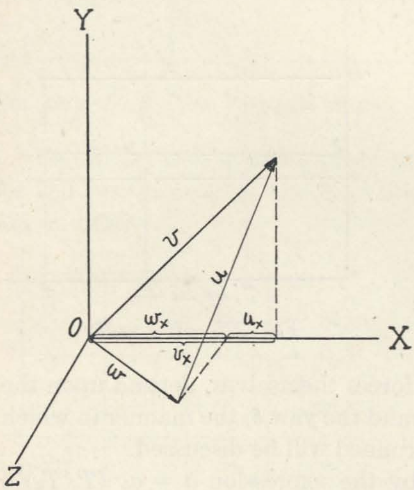


FIG. 227.—Vector Diagram of u, v, and w.

Projectiles would generally have the center of pressure ahead of the center of gravity unless devices such as fins were used to shift the center of pressure towards the base. Figure 220 shows that the air force would tend to cause such a projectile to tumble. Two devices are used to prevent the tumbling: (1) some projectiles are given a spin about the longitudinal axis and (2) fins are attached to the tails of others to bring the center of pressure to the rear of the center of gravity, making the air moment a righting instead of an overturning one and causing them to trail properly along the trajectory.

The theory by which δ and ϕ may be computed as a function of the time is the theory of the motion of a rigid body of revolution about its center of gravity. Because of restrictions of space, this theory will not be given in detail but some of the important results will be mentioned. In considering the motion of a spinning projectile about its center of gravity it is expedient to consider two regimes: (1) that where the projectile is near the gun, the curvature of the trajectory is small, and the projectile is wobbling because of the disturbances caused by its launching; (2) that at some distance from the gun, where the curvature of the

trajectory is considerable, the nutations have been damped out, and a relatively steady precessional yaw is caused by the curvature of the trajectory.

At ordinary velocities, the trajectory curves so little near the gun that, without appreciable error, it may be considered straight. Under these conditions, the behavior of the projectile may be compared to that of a top placed upon a flat smooth surface. For the top, we assume that the center of gravity is at O and the point is at P, Fig. 228. If the mass of the top is m, the smooth surface exerts a force mg upon the top, pointing vertically upwards. The component of this force acting normal to the axis of the top is $mg \sin \delta$, δ being the angle between the axis and the vertical. Therefore, the overturning moment is

$$M = \overline{PO} \cdot mg \sin \delta$$

and the moment factor μ is $\overline{PO} \cdot mg$.

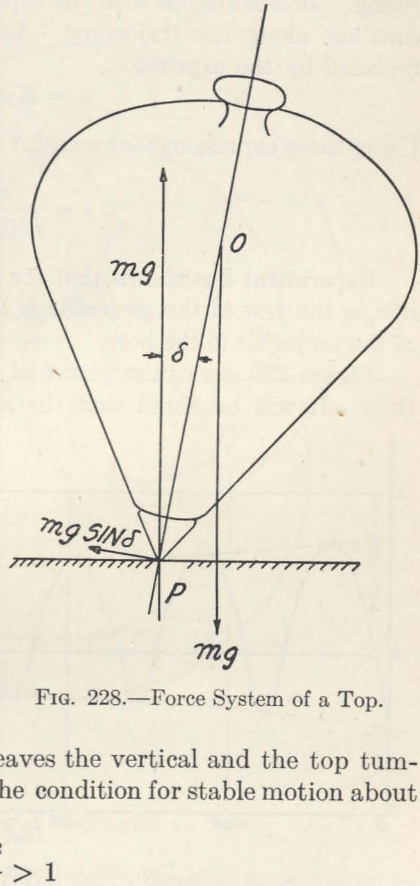


FIG. 228.—Force System of a Top.

If a top is spun rapidly enough, its axis will move for a considerable time in the vicinity of the vertical, even if it is given small blows tending to upset it. The motion of the axis of the top about the vertical is said to be stable. If the spin is insufficient, the axis leaves the vertical and the top tumbles, the motion being unstable. The condition for stable motion about the vertical exists when

$$\frac{A^2N^2}{4B\mu} > 1$$

where A is the axial moment of inertia, B the moment about a transverse axis through the center of gravity, and N the spin in radians per second.

A similar condition holds for a projectile if A, B, N, and μ are given appropriate definitions. In general, if $A^2N^2/4B\mu$ is greater than unity, the projectile will not tumble; if it is less than unity, the projectile will tumble, resulting in a loss in range and erratic flight. Because of its

great significance in this connection, the quantity $A^2N^2/4B\mu$ is designated by a special symbol s, called the *stability factor*. In practice, the twist of the rifling is designed so that s will be greater than unity.

The spin N at the muzzle is given by the expression $\frac{2\pi v_0}{nd}$, where v_0 is the muzzle velocity and n is the number of calibers for one turn of the rifling. In accordance with the experimental results, it will be taken as constant along the trajectory. As shown in Section 282, μ may be replaced by the expression,

$$\mu = K_M \rho d^3 u^2.$$

Using these expressions for μ and N, the stability factor may be written

$$s = \frac{\pi^2 A^2 v_0^2}{n^2 B K_M \rho d^5 u^2} \tag{6}$$

Experiment has shown that for most guns, the yaw near the gun is due to the yaw of the projectile in the gun resulting from the clearance of the projectile in the bore.

Figure 229 shows the yaw δ of a 3.3-in. projectile as a function of time. It will be noted that the amplitude of the nutations becomes

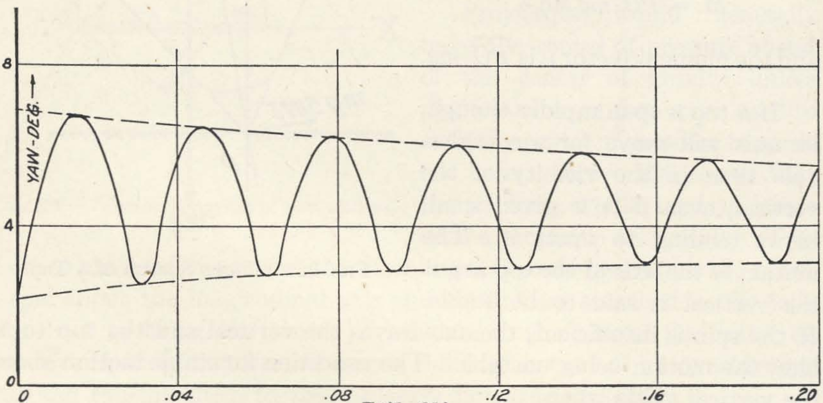


FIG. 229.—Curve of Yaw vs. Time.

smaller as t increases. Figure 230 gives a plot of ϕ, the angle of orientation, vs. δ, for the same projectile.

It can be shown that the maximum amplitude of the yaw near the gun is given by the expression,

$$\alpha = \left(2\frac{B}{A} - 1\right)\frac{\zeta}{(1 - 1/s)^{1/2}}$$

where ζ is the yaw in the gun at the muzzle. It will be noted that the amplitude α is proportional to ζ and increases rapidly as s approaches unity. The formula has no significance for $s < 1$.

As the projectile moves along the trajectory, the curvature of the trajectory becomes greater until shortly after the maximum ordinate is

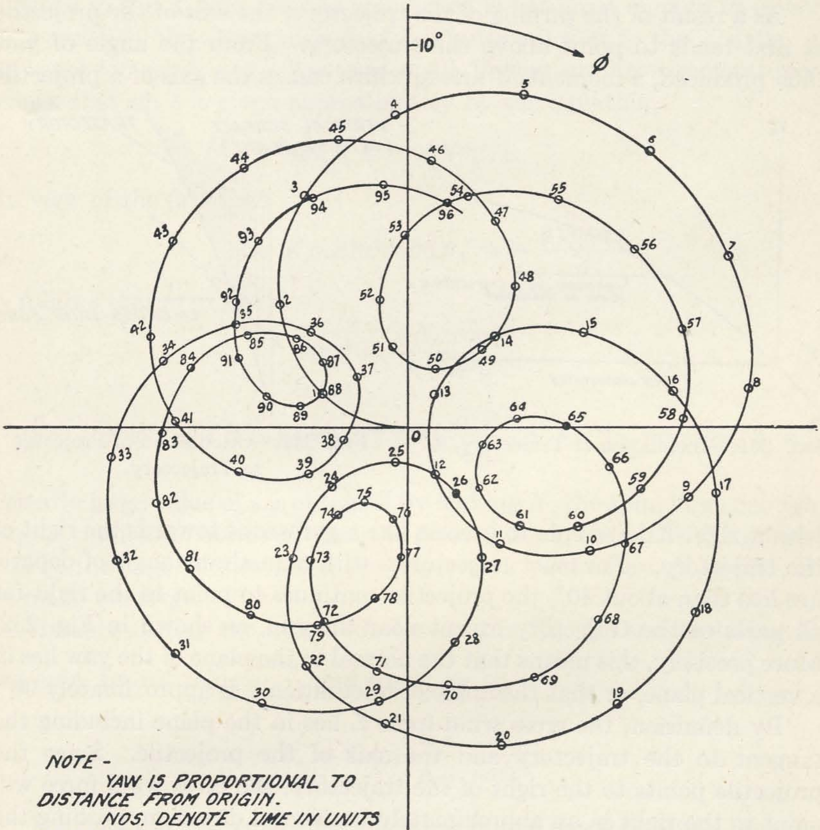


FIG. 230.—Curve of Angle of Orientation vs. Yaw.

reached. After this, the curvature diminishes again. θ_a is the angle the trajectory makes with the horizontal, referred to air coordinates, as in Fig. 231. The rate of turning of the tangent to the trajectory at the projectile, about a horizontal axis perpendicular to the trajectory, and moving with the projectile as the projectile moves along the trajectory, is $\frac{d\theta_a}{dt}$. It will be designated by θ_a'.

If the effect of the cross wind force L on θ_a' is neglected, as it may be

except for parts of trajectories fired with values of θ_0 greater than about 50°,

$$\theta_a' = -\frac{g \cos \theta_a}{u} \tag{7}$$

if the wind is constant.

As a result of the turning of the trajectory, the axis of the projectile at first tends to point above the trajectory. From the angle of yaw thus produced, a moment M arises, which causes the axis of a projectile

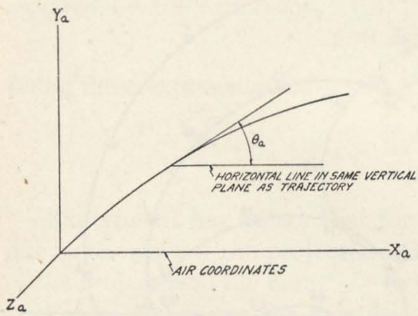


FIG. 231.—Inclination of Trajectory, θ_a.

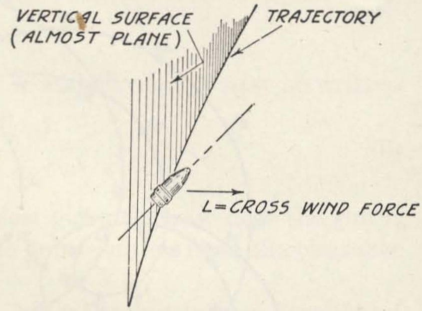


FIG. 232.—Orientation of Projectile to Trajectory.

with a right-handed spin to precess like a gyroscope towards the right of the trajectory. For most trajectories with a quadrant angle of departure less than about 40°, the projectile continues to point to the right for all parts of the trajectory except near the gun, as shown in Fig. 232. More precisely, this means that the normal to the plane of the yaw lies in a vertical plane, or that the angle of orientation ϕ is approximately 90°.

By definition, the cross wind force L lies in the plane including the tangent to the trajectory and the axis of the projectile. Since the projectile points to the right of the trajectory, the cross wind force will point to the right in an approximately horizontal direction, pushing the projectile to the right and producing the phenomenon of drift.

As the quadrant angle of departure is raised, the curvature of the trajectory near the maximum ordinate becomes greater, the angle of yaw becomes larger, and the projectile no longer points approximately to the right of the trajectory. The cross wind force is no longer directed horizontally to the right along the Z axis but has appreciable components, L_x, L_y, and L_z along all three coordinate axes.

However, for values of θ_0 below 40°, or with trajectories terminated considerably short of the maximum ordinate,

$$L_z = L = K_L \rho d^2 u^2 \sin \delta \tag{8}$$

In equating L_z to L, it is assumed that L, which is, by hypothesis, horizontal and perpendicular to the trajectory, is also perpendicular to the X axis. If the vertical plane including the tangent to the trajectory were parallel to the X axis, the assumption would be correct. As a result of wind and drift, the above-mentioned plane is usually slightly inclined to the X axis, but the inclination is not great enough to invalidate seriously the assumption that L is perpendicular to the X axis. If θ_a' is not too great, and ρ is not too small, Fowler and his associates have shown that sin δ is given approximately by the equation,

$$\sin \delta = - AN\theta_a'/\mu.$$

In view of the fact that

$$\mu = K_M\rho d^3u^2, \text{ and } \theta_a' = -\frac{g\cos\theta_a}{u}$$

it follows that

$$\sin \delta = \frac{ANg\cos\theta_a}{K_M\rho d^3u^3} \tag{9}$$

For stable flight it is necessary that $\dfrac{A^2N^2}{4B\mu} > 1$. In practice, a sufficiently large value of s is obtained by making N, the spin, large enough. Eq. (9) indicates, however, that the greater the value of N, the greater will be the angle of yaw along the trajectory. Therefore, N should not be made too large.

By substituting the expression for sin δ in Eq. (8) and replacing N, the spin, by its value $\dfrac{2\pi v_0}{nd}$, and cos θ_a by u_x/u*;

$$L_z = 2\pi gA\cdot\frac{K_L}{K_M}\cdot\frac{v_0u_x}{nd^2u^2}.$$

If ρ were much smaller than the atmospheric densities found near the earth's surface, sin δ would no longer be even approximately inversely proportional to ρ, as given by Eq. (9). Consequently the expression for L_z would not hold for such conditions. In the following it will be assumed, unless the contrary is explicitly stated, that the trajectories under discussion are those of projectiles moving in the atmosphere near the surface of the earth. From Eq. (8) it is clear that if $\rho = 0$, $L = 0$.

*Cos θ_a is exactly equal to $\dfrac{u_h}{u}$ where $u_h = (u_x{}^2 + u_z{}^2)^{\frac{1}{2}}$; or, u_h is the resultant of u_x and u_z. As a rule u_z is so small that it may be neglected in comparison with u_x without serious error.

The force L_z is the cause of the drift mentioned in Section 276. As stated above, the drift of projectiles fired from cannon having a right-hand twist of rifling is towards the right unless θ_0 is greater than about 65°. Even for such trajectories, the drift is at first towards the right; near the maximum ordinate, however, the direction of the drift changes towards the left.

The axial moment of inertia A may be written as pmd^2. For most projectiles the value of p is about 0.14. With this substitution, for all parts of trajectories with $\theta_0 < 40°$ and for all trajectories terminated considerably short of the maximum ordinate,

$$L_z = 2\pi g p \frac{K_L}{K_M} \cdot \frac{m v_0 u_x}{n u^2} \tag{10}$$

$\dfrac{K_L}{K_M}$ for the two projectile types is shown as a function of u/a in Fig. 233.

While it is true that well-designed and well-made finned projectiles will trail properly, nevertheless, in some cases, the fins are asymmetrical and exert a rudder effect. Thus a yaw of the projectile arises, and with it a cross wind force tending to displace the trajectory from that of an accurately made projectile. This phenomenon may be of considerable importance in connection with the dispersion in range and deflection of airplane bombs and of finned projectiles fired from cannon.

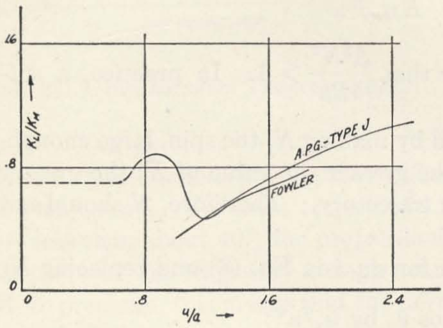


Fig. 233.—Curve Showing $\dfrac{K_L}{K_M}$ vs. $\dfrac{u}{a}$.

284. Measurement of the Coefficients, K_D, K_L, and K_M.—Although notable progress has recently been made by von Kármán, Taylor, and others in the theoretical evaluation of the drag coefficient of simple projectile shapes at zero yaw, it is still necessary to determine the drag coefficient and the other coefficients experimentally.

K_D for a given projectile is determined by measuring the velocity of the projectile at a number of points. From the drop in velocity the retardation may be determined.

If the projectile is fired along the X axis, neglecting L_x, Eqs. (2) and (3) show that

$$m \frac{dv_x}{dt} = - K_D \rho d^2 u^2 \quad \text{or} \quad K_D = - \frac{m \dfrac{dv_x}{dt}}{\rho d^2 u^2}.$$

Thus K_D, which depends upon u/a and δ, is known for the given values of u/a and δ, if the mass of the projectile m, the acceleration $\frac{dv_x}{dt}$, the air density ρ, the diameter d, and the air speed u are known. The ratio u/a is known if the temperature is known. The yaw δ may be measured approximately by cardboards or by spark photographs.

The moment coefficient K_M may be determined as follows: T, the period of the yaw of the projectile near the gun, is

$$\frac{2\pi}{\frac{AN}{B}(1 - 1/s)^{1/2}}.$$

T may be determined by recording the yaw by cardboards or spark photographs and the times at which the projectile perforates the cardboards by a suitable chronograph.

The moments of inertia, A and B, may be determined before firing and N, the spin, computed from the muzzle velocity, the diameter, and the number of calibers for one turn of the rifling, n.

It follows from Eq. (6) that

$$K_M = \frac{\pi^2 A^2 v_0^2}{sn^2 B\rho d^5 u^2}.$$

Thus K_M may be determined for the given value of u/a.

The cross wind force coefficient K_L may also be measured. Since the moment, $M = N_R \cdot \overline{OP} = \mu \sin \delta$ and $N_R = \nu \sin \delta$, where μ and ν are the moment and normal force factors respectively,

$$\mu = \nu \cdot \overline{OP}.$$

Consider two projectiles of the same shape and, hence, with the same position of the center of pressure P, but with their centers of gravity at O_1 and O_2. If μ_1 and μ_2 are the corresponding moment factors,

$$\mu_1 = \nu \cdot \overline{O_1P}, \quad \mu_2 = \nu \cdot \overline{O_2P}.$$

Hence, $\mu_2 - \mu_1 = \nu \cdot \overline{O_2P} - \nu \cdot \overline{O_1P} = \nu \cdot (\overline{O_2P} - \overline{O_1P}) = \nu \cdot \overline{O_2O_1}$ and

$$\nu = \frac{\mu_2 - \mu_1}{\overline{O_2O_1}}.$$

If two projectiles of the same shape but with different positions of O are considered, K_M can be found for each projectile as described above.

Let these be K_{M1} and K_{M2}. From these, μ_1 and μ_2 may be obtained and, hence, if $\overline{O_1O_2}$ is known from measurements of the two projectiles before firing, ν may be calculated. It has been shown that $N_R = \nu \sin \delta$, and $L = \lambda \sin \delta$. Taking the components of D and L perpendicular to the axis of the shell, as shown in Fig. 234,

$$N_R = \nu \sin \delta = D \sin \delta + L \cos \delta = D \sin \delta + \lambda \sin \delta \cos \delta.$$

Hence,

$$\lambda \cos \delta = \nu - D.$$

In this way λ, and hence K_L, may be determined from ν and D.

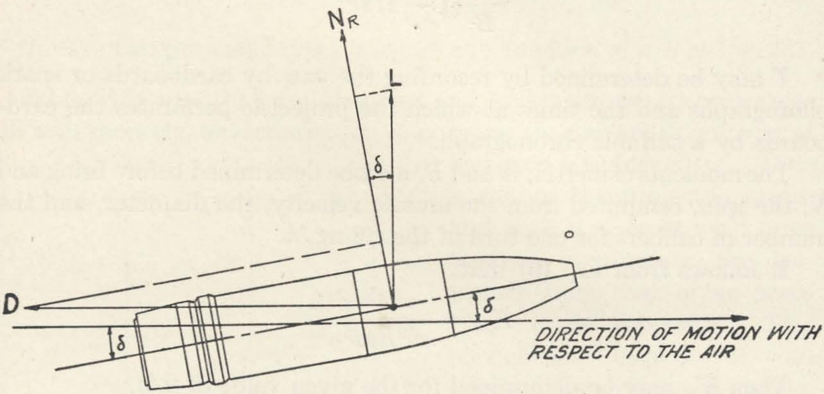


FIG. 234.—Components of D and L Perpendicular to the Axis.

The first measurements of the drag of artillery projectiles were made by Robins in 1741; Fowler and his associates made the first measurements of K_L and K_M in 1918.

285. Structure of the Atmosphere.—The manner in which the forces D, L, and the couple M depend upon the wind w, the density ρ, and the velocity of sound a has been discussed. The projectile is fired into an atmosphere, the characteristics of which vary from point to point. To calculate the forces acting on a projectile with velocity components, v_x, v_y, and v_z, with reference to the fixed coordinate system, it is, in general, necessary to know the wind components, w_x, w_y, and w_z, and also ρ and a as functions of the coordinates x, y, and z.

In general, the wind varies in direction and velocity with altitude; the air density and the velocity of sound usually diminish with altitude. They may to some extent also depend upon the horizontal components of the distance of the projectile, x and z, but it is usually assumed that they depend only upon the altitude. The dependence of these atmos-

pheric characteristics upon x, y, and z is expressed by the term *atmospheric structure.*

The wind components w_x, w_y, and w_z are determined as functions of y by sounding balloons; the density ρ by pressure and temperature measurements during an airplane flight from the level of the gun to the maximum ordinate. The temperature measurements determine the sound velocity a.

The structure of the atmosphere changes from day to day and sometimes appreciably from hour to hour. For firing tables and other purposes, it is expedient to assume a certain structure which approximates the *average* structure of the atmosphere. This assumed structure is called the *standard structure.*

Since the wind may blow in any direction, its velocity is assumed to be zero for the standard structure. The density ρ is assumed to be an exponential function of the altitude, because such a law closely approximates the average density structure and simplifies the calculation of trajectories. The sound velocity is assumed to be constant, although it usually diminishes with altitude. This assumption also simplifies the calculation of trajectories.

The standard structure is accordingly defined by the following equations:

$$w_x = w_y = w_z = 0$$
$$^*\rho = \rho_0 e^{-hy}$$
$$a = \text{Const.} = 1120 \text{ ft. per second.}$$

In the expression for ρ,

$$\rho_0 = 0.07513 \text{ lb. per ft.}^3, \quad h = 0.0000316 \ 1/\text{ft.}$$

The standard sound velocity of 1120 ft. per second is designated by a_0. The corresponding temperature is 59° F. or 518° absolute on the Fahrenheit scale. 518° is designated by T_0 and the absolute temperature of the actual atmosphere as a function of the altitude is designated by $T(y)$. As mentioned in Section 282, $a = a_0(T/T_0)^{1/2}$.

286. Components of the Forces, Drag, Cross Wind Force, and Gravity, along the Coordinate Axes.—The magnitudes of the drag D and the cross wind force L have been discussed. Their directions have merely been mentioned. D has a direction opposite to the direction of motion. Hence, if θ_{xa}, θ_{ya}, and θ_{za} are the angles the trajectory makes

* In bombing, the standard density ρ_0 is taken to hold at the point of fall, Ω, instead of at the origin, O, of the trajectory.

with the coordinate axes, X_a, Y_a, and Z_a, moving with the air at the projectile and parallel to the axes, X, Y, and Z, respectively, the components of D are shown in Fig. 235 to be $-D \cos \theta_{xa}$, $-D \cos \theta_{ya}$, and $-D \cos \theta_{za}$.

The force L is perpendicular to the trajectory in the plane of the yaw. Hence its direction depends upon the angle of orientation ϕ. In the general case, the magnitudes of δ and ϕ can be calculated only by laborious computations involving the numerical integration of six simultaneous second order differential equations, three for the motion of

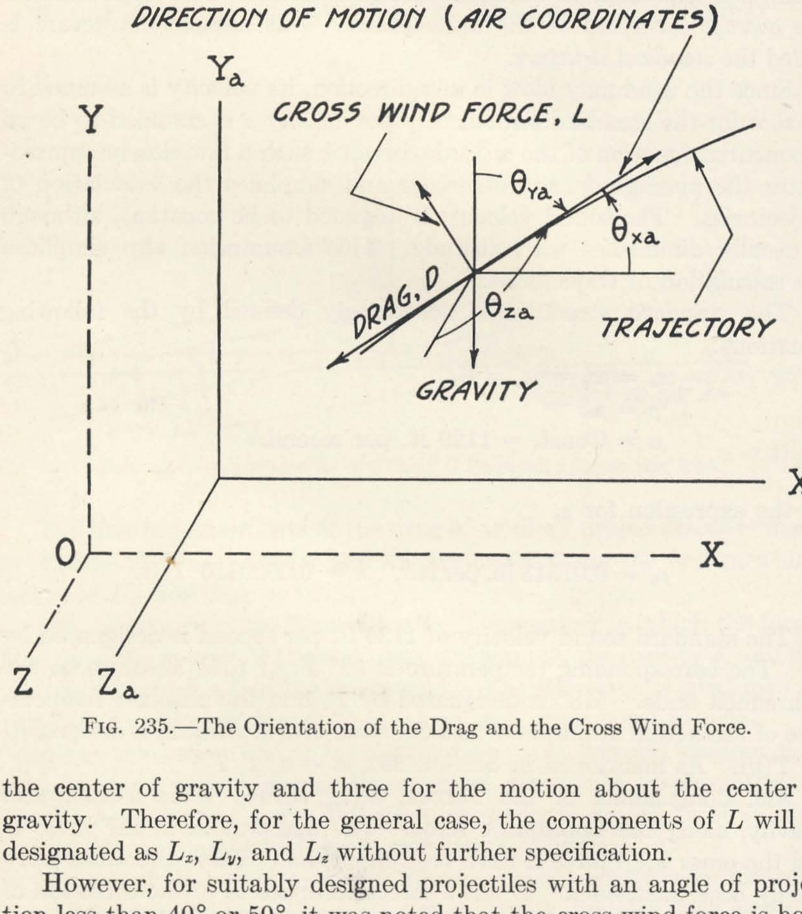


FIG. 235.—The Orientation of the Drag and the Cross Wind Force.

the center of gravity and three for the motion about the center of gravity. Therefore, for the general case, the components of L will be designated as L_x, L_y, and L_z without further specification.

However, for suitably designed projectiles with an angle of projection less than 40° or 50°, it was noted that the cross wind force is horizontal and perpendicular to the trajectory, and that it points, therefore, approximately along the Z axis. For such projectiles and trajectories, $L_z \approx L$ and $L_x \approx L_y \approx 0$, where $\approx$ means *approximately equal.*

287. The Equations of Motion.—By substitution of the above components in Eq. (2):

$$m\frac{dv_x}{dt} = -\ D \cos \theta_{xa}$$

$$m\frac{dv_y}{dt} = -\ D \cos \theta_{ya} - mg$$

$$m\frac{dv_z}{dt} = -\ D \cos \theta_{za} + L.$$

Therefore, the accelerations will be

$$\frac{dv_x}{dt} = -\frac{D}{m} \cos \theta_{xa}$$

$$\frac{dv_y}{dt} = -\frac{D}{m} \cos \theta_{ya} - g$$

$$\frac{dv_z}{dt} = -\frac{D}{m} \cos \theta_{za} + \frac{L}{m}.$$

To reduce these equations to a form more suitable for computation, the cosines, $\cos \theta_{xa}$, etc., will be expressed in terms of u, the air speed, and its components u_x, u_y, and u_z.

It may be seen from Fig. 236 that

$$\cos \theta_{xa} = \frac{u_x}{u}, \quad \cos \theta_{ya} = \frac{u_y}{u}, \quad \text{and } \cos \theta_{za} = \frac{u_z}{u}.$$

Using these relations and inserting the values of D and L from Eqs. (3) and (10), it is found that

$$\frac{dv_x}{dt} = -\frac{K_D \rho d^2 u^2}{m}\cdot\frac{u_x}{u} = -\frac{d^2\rho\cdot K_D\cdot u\cdot u_x}{m}$$

$$\frac{dv_y}{dt} = -\frac{K_D \rho d^2 u^2}{m}\cdot\frac{u_y}{u} - g = -\frac{d^2\rho\cdot K_D\cdot u\cdot u_y}{m} - g \qquad (11)$$

$$\frac{dv_z}{dt} = -\frac{K_D \rho d^2 u^2}{m}\cdot\frac{u_z}{u} + \frac{2\pi g p}{m}\cdot\frac{K_L}{K_M}\cdot\frac{m v_0 u_x}{n u^2} = -\frac{d^2\rho\cdot K_D\cdot u\cdot u_z}{m} + 2\pi g p\cdot\frac{K_L}{K_M}\frac{v_0 u_x}{n u^2}$$

Although the drag coefficient K_D has been determined for zero yaw as a function of $\frac{u}{a}$ for a number of different projectile shapes, in general,

the actual projectile fired will differ in shape from the projectiles for which K_D at zero yaw has been determined. Furthermore, if the projectile is not moving exactly nose-on, K_D will differ from that of a projectile which is moving nose-on. L_x and L_y for a spinning projectile are approximately zero when $\theta_0 < 40°$. They are not exactly zero, however, and the approximation becomes worse as θ_0 increases.

Suppose the projectile fired resembles more or less closely the projectile type J, for which the head resistance coefficient for zero yaw is

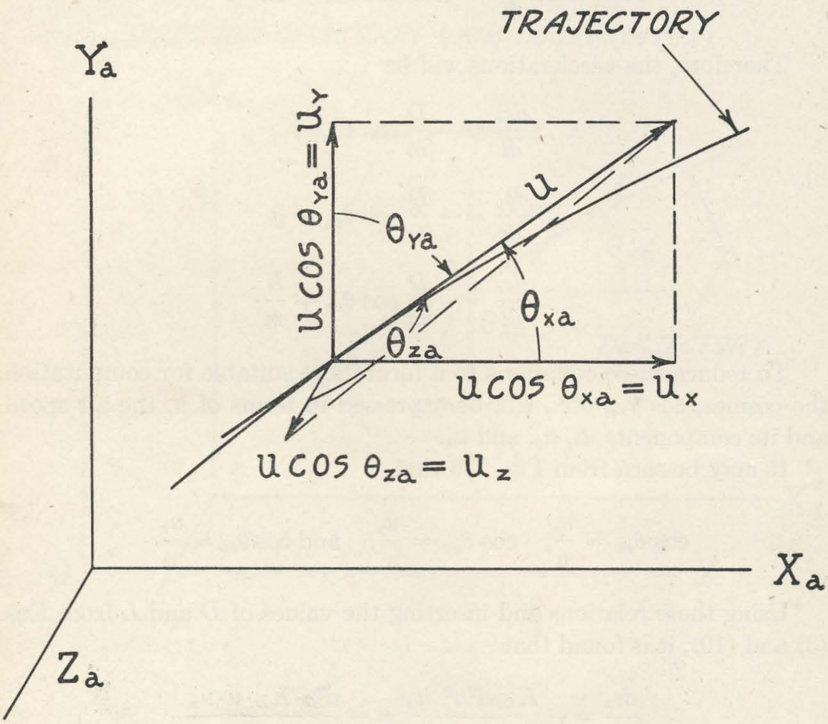


FIG. 236.—Evaluation of the Direction Cosines.

designated by K_{DJ}; it is *assumed* that the accelerations along the X and Y axes may be represented by

$$\begin{aligned} \frac{dv_x}{dt} &= -\frac{i_J d^2 \rho K_{DJ} u \cdot u_x}{m} \\ \frac{dv_y}{dt} &= -\frac{i_J d^2 \rho K_{DJ} u \cdot u_y}{m} - g \end{aligned} \tag{12}$$

In these expressions, i_J is called the *form factor* of the given projectile with respect to projectile type J. It is considered a constant for the given trajectory. The form factor i_J is introduced because the drag D and the cross wind force L of the projectile are not known. To represent approximately these unknown forces, L_x and L_y are ignored, and the drag of projectile type J, D_J, is multiplied by a factor, i_J, obtaining $i_J D_J$, in which a value of the constant i_J is sought which will represent, on the average, the accelerations of the projectile as satisfactorily as possible for the particular problem under consideration. Resort is had to such a device only because of: (1) ignorance of K_D and K_L for the projectile fired and (2) the difficulty of computing δ and ϕ accurately.

As a rule, the value of i_J chosen is based on the results of firings. If the projectile fired or its conditions of projection differ from the projectile to which a value of i_J is to be assigned, the value of i_J assigned is called an estimated one. If i_J is based on the elements of the trajectory fired with the actual projectile and the same conditions of projection, the value of i_J so determined is called the observed or empirical value of i_J. The manner in which the value of i_J may be determined from firings will be explained in Section 294. It is evident from its definition that the form factor i_J depends

(1) upon the shape of the projectile fired,
(2) upon the shape of the projectile for which the drag coefficient K_{DJ} is determined,
(3) upon the characteristics of flight of the projectile fired,
(4) upon the particular problem to be solved.

In a similar manner, the acceleration along the Z axis may be represented by

$$\frac{dv_z}{dt} = -\frac{i_J d^2 \rho K_{DJ} \cdot u \cdot u_z}{m} + 2\pi g p j_J \cdot \frac{K_{LJ}}{K_{MJ}} \cdot \frac{v_0 u_x}{n u^2} \tag{13}$$

where K_{LJ} and K_{MJ} are, respectively, the cross wind force and couple coefficient for projectile type J, and j_J is called the *drift factor*. In addition to the parameters upon which i_J depends, j_J also depends upon the position of the center of gravity.

$K_{DJ} \cdot u$ may be replaced by F_J, which is called the *drag function* of the projectile type J. $F_J(u,a) = K_{DJ} \cdot u$ is the function which expresses the resistance characteristics of the projectile type J as depending upon the air speed u and the velocity of sound a. It is determined when u and a are given. By definition, of course, K_{DJ} is obtained at zero yaw. F_J is tabulated as a function of u and a. An abbreviated table is given below.

TABLE OF VALUES OF F_J FOR VARIOUS VALUES OF u AND a

u ft. per second	a, ft. per second 1050	1100	1150
800	56	54	52
1000	105	75	67
1200	205	198	191
1400	226	221	214
1600	239	235	231
1800	246	243	240
2000	254	250	247
2200	263	258	254
2400	274	268	263
2600	286	279	273
2800	297	290	283
3000	307	300	294
3200	317	310	303

Similarly, a drift function Q_J may be established. $Q_J = \dfrac{K_{LJ}}{K_{MJ}u^2}$. This might be tabulated as depending upon u and a, as was done with F_J.

Substituting F_J for $K_{DJ} \cdot u$, Q_J for $\dfrac{K_{LJ}}{K_{MJ}u^2}$, and omitting the subscript J's from i, j, F, and Q, Eqs. (12) and (13) are reduced to the following form:

$$\frac{dv_x}{dt} = -\frac{id^2\rho F \cdot u_x}{m}$$

$$\frac{dv_y}{dt} = -\frac{id^2\rho F \cdot u_y}{m} - g$$

$$\frac{dv_z}{dt} = -\frac{id^2\rho F \cdot u_z}{m} + \frac{2\pi gpjv_0 \cdot Q \cdot u_x}{n}.$$

C is now substituted for $\dfrac{m}{id^2}$ and C_L for $\dfrac{n}{2\pi gpjv_0}$ and the equations may be written:

$$\begin{aligned} \frac{dv_x}{dt} &= -\frac{\rho F \cdot u_x}{C} \\ \frac{dv_y}{dt} &= -\frac{\rho F \cdot u_y}{C} - g \\ \frac{dv_z}{dt} &= -\frac{\rho F \cdot u_z}{C} + \frac{Q \cdot u_x}{C_L} \end{aligned} \tag{14}$$

The quantity C is called the *ballistic coefficient* and the quantity C_L the *drift coefficient.*

On the left-hand side of Eqs. (14) the accelerations are expressed with respect to the chosen coordinate axes, and on the right the velocities u_x, u_y, u_z, and u with respect to the moving air. These velocities can be referred to the coordinate axes X, Y, and Z by using the relations established in Section 282:

$$\begin{aligned} u_x &= v_x - w_x \\ u_y &= v_y - w_y \\ u_z &= v_z - w_z \\ u^2 &= u_x^2 + u_y^2 + u_z^2. \end{aligned}$$

By making these substitutions, $F \cdot u_x$, $F \cdot u_y$, $F \cdot u_z$, and $Q \cdot u_x$ depend only upon v_x, v_y, v_z, and y, since a depends only upon y, and w_x, w_y, and w_z depend only upon y. By hypothesis, ρ depends only upon y. Thus the equations satisfy the requirements mentioned in Section 277: that is, the quantities on the right-hand side depend only upon v_x, v_y, v_z, and y. It is now assumed that the simultaneous Eqs. (14) may be solved and that the solution will fit a specific problem if the initial values of v_x, v_y, v_z and x, y, and z are suitable. The following values are used in working out the solution:

$$x_0 = 0, y_0 = 0, z_0 = 0, v_{x_0} = v_0 \cos \theta_0, v_{y_0} = v_0 \sin \theta_0, v_{z_0} = 0.$$

In many instances, it is desired to calculate the range and deflection for an atmosphere of standard structure. For such an atmosphere, it was shown in Section 285 that

$$\rho = \rho_0 e^{-hy}, \quad w_x = w_y = w_z = 0.$$

Hence

$$u_x = v_x, \quad u_y = v_y, \quad u_z = v_z$$

$$u^2 = v_x^2 + v_y^2 + v_z^2 = v^2$$

and a is constant. Therefore, F and Q depend upon v only. For an atmosphere of such a structure, Eqs. (14) become

$$\begin{aligned} \frac{dv_x}{dt} &= -\frac{\rho_0 e^{-hy} F(v) \cdot v_x}{C} \\ \frac{dv_y}{dt} &= -\frac{\rho_0 e^{-hy} F(v) \cdot v_y}{C} - g \\ \frac{dv_z}{dt} &= -\frac{\rho_0 e^{-hy} F(v) \cdot v_z}{C} + \frac{Q(v) \cdot v_x}{C_L} \end{aligned} \tag{15}$$

The initial values of x, y, z, v_x, v_y, and v_z are as specified above. The third of Eqs. (15) is the equation for calculating the drift.

288. Summary of the Derivation of the Equations of Motion.—By the aid of Newton's second law, the equations of motion were shown to be

$$m\frac{dv_x}{dt} = P_x$$

$$m\frac{dv_y}{dt} = P_y$$

$$m\frac{dv_z}{dt} = P_z$$

where P_x, P_y, and P_z are the components of the total force along the three axes. It was understood that these equations could be solved if the P's were known as functions of v_x, v_y, v_z, x, y, and z.

The force components P_x, P_y, and P_z depend upon the drag D, the cross wind force L, and the weight W. The magnitudes of the forces D and L were expressed as functions of the variables ρ, d, v, u/a, and δ, and their components and those of gravity along the coordinate axes were obtained. Thus the equations of motion were reduced to the form

$$\frac{dv_x}{dt} = -\frac{d^2\rho K_D \cdot u \cdot u_x}{m}$$

$$\frac{dv_y}{dt} = -\frac{d^2\rho K_D \cdot u \cdot u_y}{m} - g$$

$$\frac{dv_z}{dt} = -\frac{d^2\rho K_D \cdot u \; u_z}{m} + 2\pi g p \frac{K_L}{K_M}\cdot\frac{v_0 u_x}{nu^2}.$$

In view of the fact that K_D and $\dfrac{K_L}{K_M}$ are frequently unknown, and of the neglect of L_x and L_y, it was assumed that the accelerations could be represented by such expressions as

$$\frac{dv_x}{dt} = -\frac{id^2\rho K_{DJ} \cdot u \cdot u_x}{m}$$

in which i is the form factor of the given projectile with respect to projectile type J and K_{DJ} is the drag coefficient of projectile type J.

On replacing $K_{DJ} \cdot u$ by F, $\frac{K_{LJ}}{K_{MJ} \cdot u^2}$ by Q, $\frac{id^2}{m}$ by $\frac{1}{C}$, and $\frac{n}{2\pi gpjv_0}$ by $\frac{1}{C_L}$, the equations were obtained in the form

$$\frac{dv_x}{dt} = -\frac{\rho F \cdot u_x}{C}$$

$$\frac{dv_y}{dt} = -\frac{\rho F \cdot u_y}{C} - g$$

$$\frac{dv_z}{dt} = -\frac{\rho F \cdot u_z}{C} + \frac{Q \cdot u_x}{C_L}.$$

It was then explained how F, Q, and the u's may be expressed in terms of the v's, the velocity components, and the w's, the wind components, which were established as functions of y, and how ρ could be expressed as a function of y. In this way the equations were reduced to such a form that they might be solved.

289. Ballistic Coefficient and Limiting Velocity.—Because of its great importance in trajectory computations, the ballistic coefficient $C = \frac{m}{id^2}$ should be discussed at greater length.

From Eqs. (14) the assumed retardation along the X axis is given by $\frac{\rho F \cdot u_x}{C}$. Thus, C is the constant by which the product, $\rho F \cdot u_x$, which is a function of y, u, and u_x, is divided to obtain the assumed retardation along the X axis, $\frac{dv_x}{dt}$.

The greater the value of C, the less the assumed retardation $\frac{dv_x}{dt}$. The less the retardation, the greater will be the range. Hence, in general, the greater the value of C, the greater will be the calculated range. The assigned magnitude of the ballistic coefficient C is therefore an estimate of the ballistic efficiency of the projectile for the particular problem under consideration.

In the preceding pages the diameter, d, was measured in feet; in actual practice in America and in England, it is usually measured in inches. Therefore, the practical ballistic coefficient is obtained from

$$C = \frac{m}{id^2}$$

where d is measured in inches, not in feet, as before.

The ballistic character of a projectile, which has been specified by

giving its ballistic coefficient, may also be stated by giving the *limiting velocity*. This is the downward velocity at which gravity would be just balanced by air resistance in air of standard density at the ground ρ_0, or, in other words, that velocity which would remain constant for a bomb falling vertically downwards in air of standard density.

If v_x, v_z, and y are placed equal to zero, Eqs. (15) become

$$\frac{dv_x}{dt} = 0$$

$$\frac{dv_y}{dt} = -\frac{\rho_0 F(v) \cdot v_y}{C} - g$$

$$\frac{dv_z}{dt} = 0.$$

If the velocity, v_y, is to be constant, $\frac{dv_y}{dt} = 0$. Accordingly, since in this case, $v = - v_y$, $vF(v) = gC/\rho_0$. This equation gives the relation between the limiting velocity v and the ballistic coefficient C.

A brief table giving C_G for certain values of the limiting velocity is appended. The subscript G is used to indicate the coefficient of a type (Gâvre) G projectile. The table illustrates the magnitude of air resistance at high velocities and also the meaning of C.

Limiting Velocity f/s	C_G
500	0.33
1000	2.12
1500	9.28
2000	15.88
2500	22.51
3000	30.26

Since the largest and heaviest projectiles rarely have a ballistic coefficient greater than 15.88, it may be seen that, even for these, air of standard density exerts a greater force on the projectile than gravity, if the velocity exceeds 2000 f/s.

In vacuum $\rho = 0$. If this value is substituted in the first two parts of Eqs. (14), and the motion in z is disregarded since the third equation does not hold for a vacuum:

$$\frac{dv_x}{dt} = 0$$
$$\frac{dv_y}{dt} = - g \qquad (16)$$

If, instead of having taken $\rho = 0$, $C = \infty$ had been used, the same Eqs. (16) would again have been obtained. Thus, if the motion in z, which has only a small effect on the range, may be neglected, the conditions $\rho = 0$ and $C = \infty$ are equivalent.

290. Computation of Trajectories.—By the computation of a trajectory is meant, in general, the preparation of a table which gives for each of a sufficient number of points on the trajectory the value of x, y, z, and t, and possibly v_x, v_y and v_z. If it were possible to write an analytic formula in terms of one of the variables for each of the others by means of a combination of familiar elementary functions, such a table could be prepared by mere substitution in the formulas. For example, it is readily shown by substitution that if $\rho = 0$, the well-known formulas for a vacuum trajectory,

$$x = v_0 t \cos \theta_0$$

$$y = v_0 t \sin \theta_0 - gt^2/2$$

constitute a solution of the first two of Eqs. (14), which is consistent with the initial conditions. Since in this case there will be no deflection ($z = 0$), the trajectory is determined. For any particular choice of values for v_0 and θ_0, such a table could be prepared by substituting in succession a number of equally spaced values of t and finding the corresponding values of x and y. Or, the equations above could be solved for t and y in terms of x and a set of equally spaced values of x substituted therein. In the case of an actual trajectory no such simple formulas can be found and the tabulations are obtained in other ways.

Early Methods.—While the impossibility of solving the ballistic problem in terms of explicit formulas is now recognized, this point of view is comparatively recent. The earliest study consisted in a search for such formulas. At that time, interest in exterior ballistics was largely academic, the subject being developed by mathematicians because they found it interesting, not because the results were needed for gunnery purposes. On the other hand, the formulation of the problem corresponded to the state of the art. Projectiles, if they were of regular shape at all, were spherical. Velocities and maximum ordinates were relatively small. No such phenomenon as drift occurred and little or no thought was given to change in air density with altitude. Long after these early conditions ceased to apply, they continued to exert a strong influence on the method of attack on the trajectory problem.

With these conditions and Newton's hypothesis that air resistance is proportional to the square of the velocity, together with the assumption

of still air, it was found possible to obtain from the equations of motion a single equation

$$\frac{dv_x}{v_x^3} = k \sec^3 \theta \, d\theta,$$

where k is a constant for the projectile, and θ is the variable angle that a tangent to the trajectory makes with the horizontal. The equation is derived on the assumption that ρ and K_D are constant, by dividing the first of Eqs. (15) by the equivalent of Eq. (7) for still air with $\theta = \theta_a$ and $v_x = u_x$. If a differential equation is reducible like this to a form in which one variable (here v_x) appears only on one side of the equation and one other (here θ) appears only on the other, it is said to have *separable variables.*

If both sides of this equation are integrated, it appears in the form

$$\int \frac{dv_x}{v_x^3} = k \int \sec^3 \theta \, d\theta.$$

Here, if the integration is carried from the point of departure to any point on the trajectory, the left side may be written $1/2v_{x_0}^2 - 1/2v_x^2$. The right side can also be expressed in terms of elementary functions, but not as simply. However, it can be written

$$\int_{\theta_0}^{\theta} \sec^3 \theta \, d\theta = \int_{\theta_0}^{0} \sec^3 \theta \, d\theta + \int_{0}^{\theta} \sec^3 \theta \, d\theta$$

$$= \int_{0}^{\theta} \sec^3 \theta \, d\theta - \int_{0}^{\theta_0} \sec^3 \theta \, d\theta.$$

It will be noted that the second term is merely a special case of the first term with the variable θ replaced by the particular value θ_0. If, then,

$$\int_{0}^{\theta} \sec^3 \theta \, d\theta$$

be computed and tabulated as a function of θ, the required expression can always be evaluated merely as the difference between two values in the table. The evaluation of such an integral, namely, one with only a known function of the variable of integration under the integral sign, is called a *quadrature*, and can be readily carried out numerically by Simpson's rule or one similar to it.

Nearly all the methods of dealing with the differential equations of a trajectory except the most recent have sought to express the solution in

terms of quadratures. The particular method of solution here referred to was devised by the Swiss, Bernoulli, in 1719. The Bernoulli method is equally applicable if the air resistance or drag is assumed equal to the cube of the velocity or any other power instead of the square. In any case, the solution can be obtained by finding t, x, and y in terms of successive quadratures.

The Mayevski Law of Resistance.—With the introduction of rifling and the use of elongated projectiles, it became necessary to make an experimental study of the law of resistance for these new projectiles. The firings conducted by the Gâvre Commission in France, the Krupps in Germany, and others showed that the resistance could by no means be taken as proportional to the square or to any other single power of the velocity. It was found by the Russian, Mayevski, however, that it was possible to express the retardation as proportional to a power of the velocity, in a restricted velocity zone. Thus, a good agreement with the experimental firings could be obtained if the retardation was written in the form $A_n v^n$, where n and A_n are constant but apply only in a restricted velocity zone. Thus $n = 2$ from the lowest velocity used in gunnery up to 790 ft. per second; $n = 3$ from 790 ft. per second to 970 ft. per second; and so on; and A_n is different in each zone, but the values are so chosen that consistent results are obtained at the junction points. The values of A_n were obtained explicitly for a standard projectile, and the results were applied to projectiles of different size and weight by means of a ballistic coefficient on the order of the one discussed in Section 289.

The method of computation was to use the Bernoulli solution to carry the trajectory from the muzzle to the point where the velocity had dropped off to the limiting value between two zones, then to use the results of this as initial conditions for the next lower zone, and so on. The results were still expressed in terms of quadratures, but a new set of quadratures was introduced for each zone. This last fact made the method less convenient to use. Moreover, no provision was made for the variation of density with altitude. Various methods attempting to meet, in part, one or both of these objections were developed toward the end of the nineteenth century and the beginning of the twentieth. Of these the most generally useful for ordinary gun fire was that bearing the name of the Italian, Siacci.

The Siacci Method.—In this the differential equations are modified for the express purpose of making it possible to solve them in terms of quadratures; and this now means one set of quadratures for the whole trajectory. The modification is dependent upon the introduction of a new independent variable called the *pseudo-velocity,* which is defined as

the vertical projection of the actual velocity on the line of departure. If this is called w_p, then

$$w_p = v_x \sec \theta_0 = v \cos \theta \cdot \sec \theta_0.$$

Clearly w_p is equal to v at the muzzle, becomes greater than v and remains so until the point on the descending branch is reached where $\theta = -\theta_0$, and thereafter is less than v. From the first two of Eqs. (14) it is easy to derive, assuming no wind, a new set in which w_p is the independent variable. Among these is

$$\frac{dx}{dw_p} = -\frac{C \cos \theta_0}{\rho F(v)}.$$

The others that are used agree with this in containing the expression $\rho F(v)$ in the denominator. The Siacci modification alters this expression in such a way as to make it depend only on w_p. Except near the velocity of sound, $F(v)$ is approximately proportional to v. On the basis of this approximation $F(v)$, which is equal to $F(w_p \cos \theta_0 \cdot \sec \theta)$, may be replaced by $\cos \theta_0 \cdot \sec \theta \cdot F(w_p)$. Now $\sec \theta$ is always greater than unity and ρ is less than ρ_0, its value at the ground. If then $\sec \theta$ is omitted and ρ is replaced by ρ_0, one of these alterations tends to decrease the denominator and the other to increase it, and the two tend to cancel each other. The substitution, however, eliminates every variable but w_p on the right side and, hence, makes it possible to obtain x as a quadrature, namely:

$$x = -\frac{C \cos \theta_0}{\rho_0} \int \frac{dw_p}{F(w_p)}.$$

By a somewhat similar procedure the rest of the solution is expressed in quadratures in terms of w_p, the pseudo-velocity. This means that it is possible to prepare a set of tables, having w_p as an argument, from which, by mere entry in the tables, the conditions at any point on the trajectory may be found without reference to any intermediate points, if the initial conditions and ballistic coefficient are known.

Actual tables suitable for practical use, however, are not quite as simple as might be inferred from the foregoing. The preparation of such tables and the general development of the Siacci method in this country is due to Ingalls, the tables being known as Ingalls' Tables, or Artillery Circular M. Their use for ordinary gun fire was standard practice in this country up to the time of the World War, and these tables or similar ones were extensively used elsewhere. They are practically free from error for ground fire at quadrant elevations up to 5°, and still constitute a very useful approximation up to 15°.

Short-arc Method.—The approximations of the Siacci method fail completely for antiaircraft and other high angle fire. At Gâvre in 1887, the Frenchman, Gossot, began the development of a method originally suggested by Euler in 1753, known as the short-arc method. This method was further developed by the Frenchmen, Garnier, Haag, and Marcus during the World War, and was applied in this country by Hamilton.

The short-arc method makes use of the Bernoulli solution but applies it only to an arc of the trajectory short enough so that the two following assumptions can be made without appreciable error. The first is that the density is constant; the second is either that the drag coefficient K_D is constant, or that the velocity remains within one of the Mayevski zones so that n and A_n are unchanged. In either case the Bernoulli method is applied to the short arc. The final conditions thus obtained for this arc become the initial conditions for the next arc, and the whole trajectory is obtained by putting together the results for the successively obtained short arcs. As may be imagined, the labor in this method is great; but it is capable of giving correct results for trajectories with high angles and high muzzle velocities, which the older methods could not give.

Numerical Integration.—This method not only provides for perfect generality in the differential equations, thus allowing the introduction of the results of any experimental or mathematical developments as they may appear, but also is somewhat less laborious than the short-arc method. It is in some respects allied to the short-arc method and the names are often used interchangeably. The two agree in making use of a large number of small steps. The flexibility of the method of numerical integration, however, constitutes a great superiority. Although the method originated in England, the particular form in which it has been most used in this country is due to Moulton. In this, t is taken as the independent variable. Since the World War, numerical integration has been the principal method used in this country for basic data. For this reason an endeavor will be made here to present a brief account of its fundamental principles.

The essential feature of the method is to find values for each of the variables at a number of points on the trajectory spaced rather closely together and, in general, at equal intervals. At each point the procedure is one of successive approximations consisting of the following steps:

(*a*) to estimate by means of their previous differences the values of the accelerations, $\frac{dv_x}{dt}$, $\frac{dv_y}{dt}$, $\frac{dv_z}{dt}$;

(*b*) by a process of quadrature to obtain successively the velocities and the coordinates;

(*c*) by substituting these in the differential equations to obtain revised values for the accelerations;

(*d*) to repeat the quadratures with these revised values;

(*e*) to continue alternately the substitution and integration until no further significant change occurs.

Since the method makes extensive use of tabular differences, some of their properties will be described. If $E(t)$ is a function of t given by some simple formula such as,

$$E(t) = (2t^3 - 15t^2 + 25t + 15)/10$$

then $E(t)$ may be listed against t for a selected set of values of t as in the accompanying table. This table contains also several successive orders of tabular differences.

t	$E(t)$	Δ'	Δ''	Δ'''
0.0	1.50			
		0.90		
0.5	2.40		−0.60	
		0.30		0.15
1.0	2.70		−0.45	
		−0.15		0.15
1.5	2.55		−0.30	
		−0.45		0.15
2.0	2.10		−0.15	
		−0.60		0.15
2.5	1.50		0.00	
		−0.60		0.15
3.0	0.90		0.15	
		−0.45		0.15
3.5	0.45		0.30	
		−0.15		0.15
4.0	0.30		0.45	
		0.30		
4.5	0.60			

Thus under Δ' appear the differences for $E(t)$, that is, the result of subtracting algebraically from a particular value of $E(t)$ the value immediately preceding it. In the same way Δ'' signifies the tabular differences of Δ', and Δ''' those of Δ''. In the particular function listed, Δ''' is a constant. This, of course, would not be true in general.

The function, $E(t)$, is plotted in Fig. 237. Obviously for an interval for which Δ' is positive, the curve rises, and where Δ' is negative, it falls. Also where Δ'' is positive, the curve is bending upward and consequently falls below the straight line joining the ends of the interval as at FG; but where Δ'' is negative, the curve is above the straight line as at DH.

The tabular differences just discussed are used in two different ways. The first of these is in the preliminary extrapolation. Let h denote the common interval between successive values of t. In the example

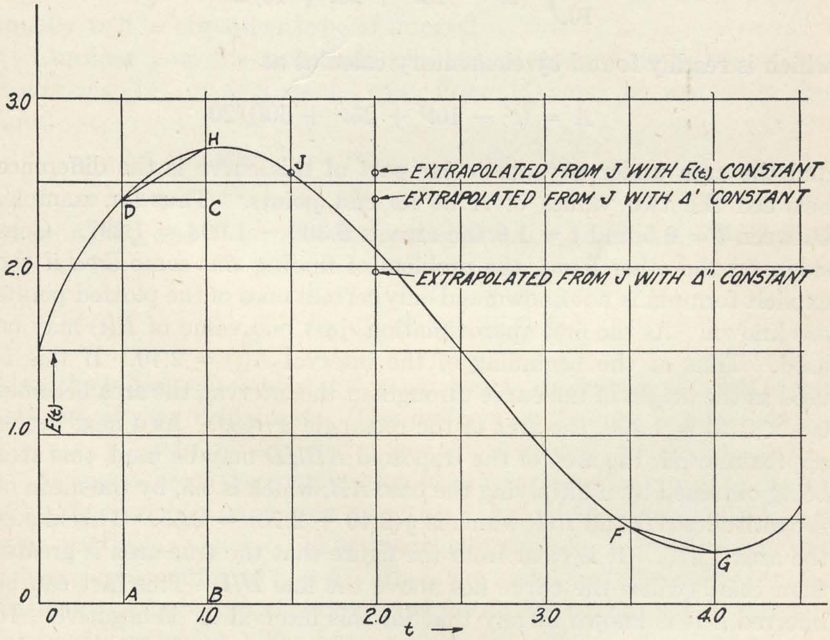


FIG. 237.—Illustration of Extrapolation and Approximate Integration.

$h = 0.5$. If the values of $E(t)$ are known up to a particular point t_0 the value of $E(t_0 + h)$ may be estimated more or less correctly by a process of extrapolation. Thus, in the example, $E(1.5) = 2.55$. The crudest sort of extrapolation would assign the same value to $E(2.0)$. This assumes that Δ', the first order difference, is zero. It would be more accurate to assume that $\Delta'' = 0$, or that Δ' retains its last previous value. In the example, this would make $E(2.0) = 2.55 - 0.15 = 2.40$. Still better would be the assumption that $\Delta''' = 0$ so that Δ'' retains its last previous value. In the example this would make $\Delta' = -0.15 - 0.45 = -0.60$, and hence $E(2.0) = 2.55 - 0.60 = 1.95$. These various approximations to the correct value, 2.10, are indicated in Fig. 237.

Since the process of extrapolation is used only to obtain a first approximation, it is not necessary to use any great refinement on it.

More important is the application of differences to the quadrature process. Consider the problem of finding the area under the curve of Fig. 237. This is, of course, $\int E(t)\,dt$; and since there is here an explicit formula for $E(t)$, this becomes

$$\frac{1}{10}\int (2t^3 - 15t^2 + 25t + 15)dt$$

which is readily found by elementary calculus as

$$A = (t^4 - 10t^3 + 25t^2 + 30t)/20$$

and the area under any particular part of this curve is the difference between the two values of A at its end points. Thus for example, between $t = 0.5$ and $t = 1.0$ the area is $2.300 - 1.003 = 1.297$. Consider, on the other hand, the problem of finding this same area if the explicit formula is not known and only certain ones of the plotted points are known. As the first approximation, just one value of $E(t)$ may be used. Thus at the beginning of the interval $E(t) = 2.40$. If this is used as the height of the curve throughout the interval, the area becomes $0.5 \times 2.40 = 1.200$, the area of the rectangle $ABCD$. As a next better approximation, the area of the trapezoid $ABHD$ may be used, this area being obtained by multiplying the base AB, which is 0.5, by the mean of the altitudes AD and BH, which is $\frac{1}{2}(2.40 + 2.70) = 2.55$. This makes the area 1.275. It is clear from the figure that the true area is greater than this because the curve lies above the line DH. This fact can be inferred if it is known merely that for this interval Δ'' is negative. In the interval from $t = 3.5$ to $t = 4.0$, on the other hand, Δ'' is positive and the area is less than that under the straight line FG. It is clear, then, that to improve the approximation it is necessary to add something when Δ'' is negative and subtract something when Δ'' is positive; that is, presumably, to subtract some multiple of Δ''. A formula incorporating this multiple and also involving a difference of the third order is

$$\int_{t_1}^{t_2} E(t)dt = (t_2 - t_1)\cdot[(E_1 + E_2)/2 - \Delta''/12 - \Delta'''/24] \qquad (17)$$

where E_1 and E_2 correspond respectively to t_1 and t_2. For accurate results, the particular values of Δ'' and Δ''' must be specified, and possibly higher order differences used. It is clear, however, that in the particular example the use of either one of the neighboring values of Δ'',

namely -0.60 or -0.45, greatly improves the approximation, since the first yields 1.300 and the second 1.294.

The general result that has been obtained so far is a method for finding an integral from a relatively small number of values of the integrand, by a method which does not require all the values to be known in advance, but provides for their use as they are determined step by step. Of course the preceding discussion has used for an illustration an area expressed as $\int E(t)dt$. The results, however, are clearly applicable equally well to any other type of integral.

Consider now the particular problem of computing a trajectory. Equations (14), or as a special case, Eqs. (15), may be written in the form

$$\frac{dv_x}{dt} = E_x, \quad \frac{dv_y}{dt} = E_y, \quad \frac{dv_z}{dt} = E_z \tag{18}$$

where E_x, E_y, and E_z are known functions of v_x, v_y, v_z, and y. By definition we have

$$\frac{dx}{dt} = v_x, \quad \frac{dy}{dt} = v_y, \quad \frac{dz}{dt} = v_z.$$

Also, the initial values of x, y, z, v_x, v_y, and v_z are known, the first three and last always being zero. The problem is to form a table giving x, y, z, v_x, v_y, and v_z for specified values of t, in general, equally spaced.

At any stage of the computation it may be assumed that the values of all the variables have been listed for values of t up to and including some particular value, t_0. The immediate problem then is to find the values corresponding to $t_0 + h$. These are found by successive approximations, the first approximation being for E_x, by means of extrapolation as already explained. The first equation of (18) may be rewritten as

$$v_x = \int E_x(t)dt$$

in general, and in particular

$$v_x(t_0 + h) = v_x(t_0) + \int_{t_0}^{t_0+h} E(t)dt.$$

This may be evaluated by the integration formula, Eq. (17), with t_1, t_2, E_1, and E_2, replaced by t_0, $t_0 + h$, $E_x(t_0)$, and $E_x(t_0 + h)$, respectively. $v_y(t_0 + h)$ and $v_z(t_0 + h)$ are obtained in the same way. Likewise, to obtain $x(t_0 + h)$, we rewrite the differential equation for x as

$$x(t_0 + h) = x(t_0) + \int_{t_0}^{t_0+h} v_x(t)dt.$$

Here no preliminary extrapolation is necessary since a value for $v_x(t_0 + h)$ has just been found by integration. Consequently the integration formula Eq. (17) may be applied at once to find $x(t_0 + h)$, and similarly to find $y(t_0 + h)$ and $z(t_0 + h)$. The values for $v_x(t_0 + h)$, $v_y(t_0 + h)$, $v_z(t_0 + h)$, and $y(t_0 + h)$ are now substituted in E_x, etc., to obtain $E_x(t_0 + h)$, $E_y(t_0 + h)$, and $E_z(t_0 + h)$, and these values are used to replace the original extrapolated ones. In any case, where the new value is the same as that first obtained by extrapolation, this value is accounted correct. If the new value is different, it is used to replace the old wherever it has been used. In this case the integration is revised, and if necessary a new substitution made in E_x, etc.

The process of alternate integration and substitution is continued until it produces no further change in the decimal places that are retained. When this occurs, the computation for this step is finished and a new step may be started from the values thus obtained. The process is repeated until the trajectory is carried as far as may be desired. With a suitably chosen value of h, there is, in most parts of the trajectory, little revision, the original estimated values frequently remaining unchanged. At the very beginning of the computation, conditions are exceptional because of the absence of some or all of the required tabular differences. This difficulty may be met either by some special device or by the use of a very short interval for a few steps. For the trajectory as a whole, the suitable length for a step varies widely with velocity and ballistic coefficient. It is, however, rarely less than 0.1 second or greater than 2 seconds in practice.

The computation of a trajectory is a long and tedious piece of work; but not so long as might be inferred from the description, since there are certain abbreviations not described. For example, in practice the motion in x and y is usually computed independently of the motion in z. Except for cases such as firing with a strong cross wind, u_z is negligible compared with u_x and u_y. Thus, the first two of Eqs. (18) contain neither z nor u_z and are integrated independently of the third. The third equation may then be readily integrated by inserting the values of u_x, u_y, and y obtained from the first two.

The accuracy of the computation may be made as great as is desired by a suitable choice of interval. In practice it is regularly made considerably greater than the accuracy required by the observational data. This is to make sure that no errors of computation are added to the unavoidable errors in observation.

Mechanical Integration.—Of equal generality with numerical integration is the solution of a system of differential equations by mechanical means. Various types of mechanical units are capable of performing

the operation of integration. Other mechanical devices can be used to connect these and to perform the simple arithmetic operations indicated in the differential equations. Within the past decade, Bush has succeeded in combining such devices into a computing machine which can be made to generate, with a satisfactory degree of accuracy, the numerical solutions of differential equations which correspond to the initial and other conditions set into it. The use of this machine in working trajectories eliminates a great amount of routine computation and enables the results to be obtained in a comparatively short time.

291. Comparison of Computed and Observed Ranges and Drifts.—In most instances, the projectiles actually used differ appreciably in shape from those for which the coefficients K_D, K_L, and K_M, or the ballistic function $F(u)$, and the drift function $Q(u)$ have been determined. Firings have been made, however, of projectiles of shapes for which $F(u)$ or $Q(u)$ have been determined. The comparison of the calculated range, using $F(u)$, with the observed range and of the calculated drift, using $Q(u)$, with the observed drift afford a test of the adequacy of the theory.

In the following tables are given the observed mean ranges of a projectile having very nearly the shape of the type J projectile, and those calculated under the same initial conditions using Eqs. (14) and a form factor $i_J = 1$.

OBSERVED AND COMPUTED RANGES OF 4.7-IN. PROJECTILE

Date 1923	Initial Conditions		Mean * Obs. Range, Yd.	Computed Range, Yd.	Diff., Yd.	Error in C, %	Probable Error of Mean Obs. Range, Yd.
	θ_0	Mean v_0					
11/18	20°	2457	14,721	14,540	181	2.4	20
11/19	19°15′	2409	14,240	14,089	151	2.3	15
11/14	44°55′	2464	20,803	20,360	443	3.7	22
11/20	44°58′	2401	19,266	19,016	250	2.3	21

* Mean observed ranges were obtained from 5-round groups.

It will be noted that, although there is an average error of 2.7 per cent in C and, hence, also in the form factor i_J, the error varies but slightly for the four groups. Thus if i_J had been taken as 0.973, instead of 1.00, the agreement between the observed and computed ranges would have been very close for all four groups in spite of the considerable variation in θ_0 and of the fact that the groups were fired on different days.

A comparison has been made of the drift calculated essentially according to Eqs. (14) and of the observed drift by Fowler and his associates. The calculations were based on the values of $\frac{K_L}{K_M}$ shown in Fig. 233 and the measured values of A and n, with a unit drift factor j. The results are reproduced in the following table:

CALCULATED AND OBSERVED DRIFT OF 3-IN. SHELL (IN MILS)

θ_0	Rifling 1/30			Rifling 1/40			Months of Firing 1918
	t_ω	Drift		t_ω	Drift		
		Obs.	Computed		Obs.	Computed	
50°	10.9	4.7	4.1	10.2	3.6	2.7	
	23.9	15.9	16.2	22.9	8.8	11.3	April–May
	33.3	28.5	28.1	31.0	17.9	19.3	
	41.3	38.7	41.1	39.1	23.2	28.3	
50°	6.99	9.4	1.8	6.33	6.8	1.2	
	15.03	7.5	7.4	14.07	5.8	4.9	February
	26.08	15.4	19.0	24.93	10.9	13.7	
30°	10.04	2.9	3.1	9.58	4.6	2.2	
	20.6	9.6	10.8	19.35	4.6	7.3	April–May
	27.9	17.3	17.0	25.95	8.0	11.5	
30°	13.2	5.5	5.2	13.02	6.7	3.7	February
	22.52	9.1	12.4	22.05	8.2	9.0	

On the average the agreement is satisfactory. The discrepancies for some of the individual measurements are due largely to failure to allow accurately for the wind. The magnitude of the deflection due to wind is usually much larger than that due to drift.

292. Exterior Ballistic Tables.—One of the problems most frequently encountered in exterior ballistics is the determination of one or more of the elements of the trajectory of a projectile for which the initial conditions θ_0 and v_0, and the ballistic coefficient C, are given.

Among these elements are

x_ω	the horizontal range	ω	the angle of fall
t_ω	the time of flight	v_ω	the striking velocity.

To reduce the labor of calculating a trajectory each time such a problem is encountered, there have been constructed ballistic tables which

contain, in condensed form, the results of the computations of a large assortment of trajectories.

In calculating trajectories for ballistic tables, the standard air structure, $\rho = \rho_0 e^{-hy}$, $w = 0$, a = constant = a_0, a given ballistic function $F(v)$, and a given altitude of the point of fall, usually $y_\omega = 0$, are frequently assumed. In horizontal flight bombing, however, the assumption is not that $y_\omega = 0$, but that $\theta_0 = 0$; the terminal elements are computed as functions of the arguments, v_0 and y_ω. That these assumptions are made, is expressed by the statement that *ballistic table conditions* hold.

When ballistic table conditions are assumed, if the motion in z is ignored, the trajectory can be determined from Eqs. (15) when θ_0, v_0, and C are given. As a result of the computation of a great number of trajectories with various values of θ_0, v_0, and C, it is possible to tabulate the terminal elements x_ω, t_ω, etc., as depending upon θ_0, v_0, and C. If it is desired to know an element of a trajectory for given values of θ_0, v_0, and C, it may then be obtained from the table without computing the trajectory. Such a tabulation of x_ω, t_ω, etc., as depending upon θ_0, v_0, and C, is called a *ballistic table*. A brief excerpt from such a table is given below.

COMPACT BALLISTIC TABLE

RANGE IN YARDS FOR VARIOUS VALUES OF θ_0, v_0, AND C

v_0 ft./sec.	C						
	2	4	6	8	10	12	14
$\theta_0 = 15°$ 1000	4,105	4,534	4,713	4,816	4,882	4,927	4,961
1500	6,035	7,406	8,204	8,749	9,147	9,453	9,695
2000	7,640	10,163	11,853	13,106	14,061	14,807	15,409
2500	9,167	12,937	15,680	17,809	19,478	20,815	21,909
3000	10,603	15,657	19,548	22,675	25,189	27,237	28,939
$\theta_0 = 30°$ 1000	6,383	7,365	7,799	8,047	8,209	8,321	8,405
1500	8,895	11,351	12,786	13,782	14,522	15,104	15,575
2000	10,756	14,721	17,391	19,431	21,075	22,438	23,591
2500	12,488	18,072	22,207	25,616	28,503	30,961	33,060
3000	14,132	21,436	27,283	32,403	36,862	40,672	43,949
$\theta_0 = 45°$ 1000	7,038	8,305	8,865	9,186	9,393	9,537	9,645
1500	9,798	12,867	14,661	15,888	16,791	17,490	18,051
2000	11,764	16,617	19,874	22,314	24,234	25,803	
2500	13,595	20,384	25,398	29,427	32,793		
3000	15,359	24,288	31,472	37,715			

Such trajectory data are sometimes also presented in the form of graphs, of which those given in Figs. 238 to 246 are examples. Such graphs are very useful and convenient for the purpose of deducing trends, and for comparing the trajectories produced by different projectiles and launching conditions. If their size is kept conveniently small, however, the elements cannot be read from them with sufficient accuracy to use in making the more precise ballistic computations.

In using such tables an approximately accurate value of C must be used if it is desired to obtain an accurate estimate of the elements of the

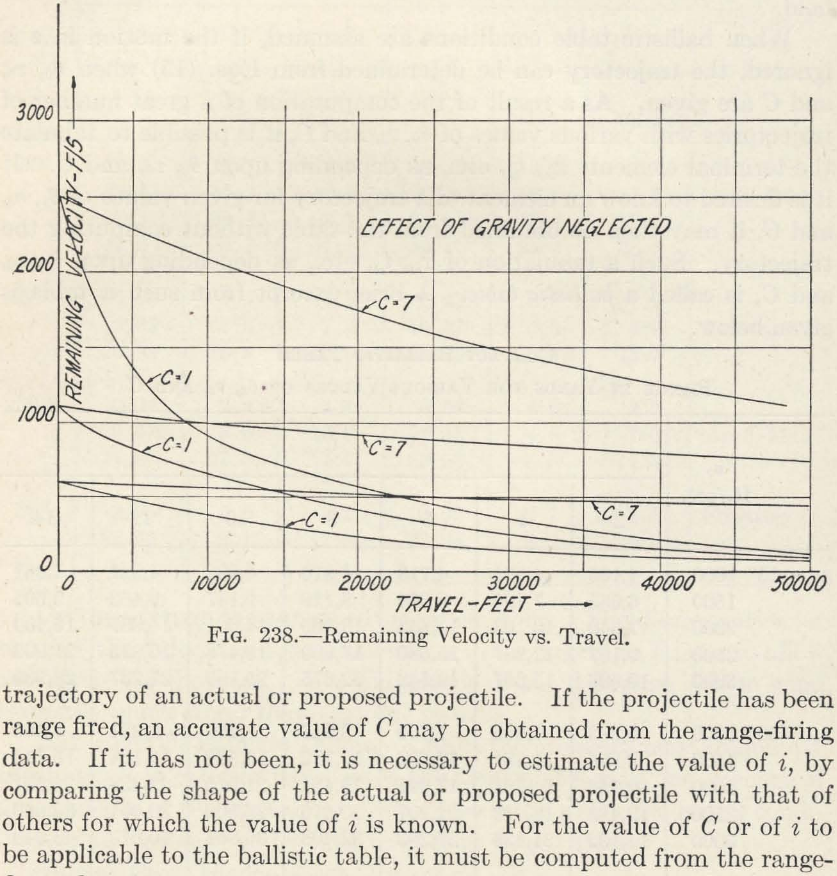


FIG. 238.—Remaining Velocity vs. Travel.

trajectory of an actual or proposed projectile. If the projectile has been range fired, an accurate value of C may be obtained from the range-firing data. If it has not been, it is necessary to estimate the value of i, by comparing the shape of the actual or proposed projectile with that of others for which the value of i is known. For the value of C or of i to be applicable to the ballistic table, it must be computed from the range-firing data by means of the same ballistic function, $F(u)$, that was used in computing the trajectories of the ballistic table.

Most, if not all, of the ballistic tables now available are based on the ballistic functions, $F(v)$, or resistance coefficient, $K_D\left(\frac{v}{a}\right)$, which apply to

flat-based projectiles having a radius of ogive of about 2 calibers. In view of the fact that most modern projectiles have much sharper noses, such tables are used only for lack of ones based on modern projectile shapes. When such tables are used, the ballistic table conditions assumed in their computation should be carefully noted and given due consideration.

293. Discussion of the Characteristics of Trajectories.—In developing the tactical use of a weapon and its ammunition, and particularly in determining the specifications for new developments, careful consideration should be given to the characteristics of the trajectories that are produced by various combinations of initial conditions v_0 and θ_0, and by other conditions expressed by the ballistic coefficient C. A few of the most important of these characteristics and the conditions which determine them will be discussed briefly.

Figure 238 shows the effect of air resistance in diminishing the velocity of a projectile under various conditions. In computing the remaining velocities, a constant air density was assumed and the effect of gravity was neglected. These curves show clearly that at relatively low initial velocities, such as those given by the lower zone charges of field howitzers, the loss of velocity due to air resistance is relatively small as compared with that which is produced when the initial velocities are relatively high. They also show that the effect of the ballistic coefficient* increases as the initial velocity increases. Since the ballistic coefficient is equal to

$$\frac{m}{id^2}$$

it is evident that projectiles to be fired with high initial velocities should be made as heavy as other conditions will permit, and should be given a shape which is aerodynamically as efficient as possible. Unless this is done, the effect of the higher initial velocity may be lost after the projectile has traveled a comparatively short distance. For instance, according to Fig. 238, a projectile having a ballistic coefficient of 1 and starting out with a velocity of 2500 ft. per second will have less velocity after traveling 10,000 ft. than one starting with a velocity of only 1100 ft. per second but having a ballistic coefficient of 7. Similarly, a projectile with a $C = 1$ and $v_0 = 1100$ ft. per second will, after traveling some 14,000 ft., be moving more slowly than one for which $C = 7$ and $v_0 = 600$ ft. per second, and which has traveled the same distance.

* For all the figures in this section except Fig. 239, the ballistic coefficient for the type G projectile, C_G, is used.

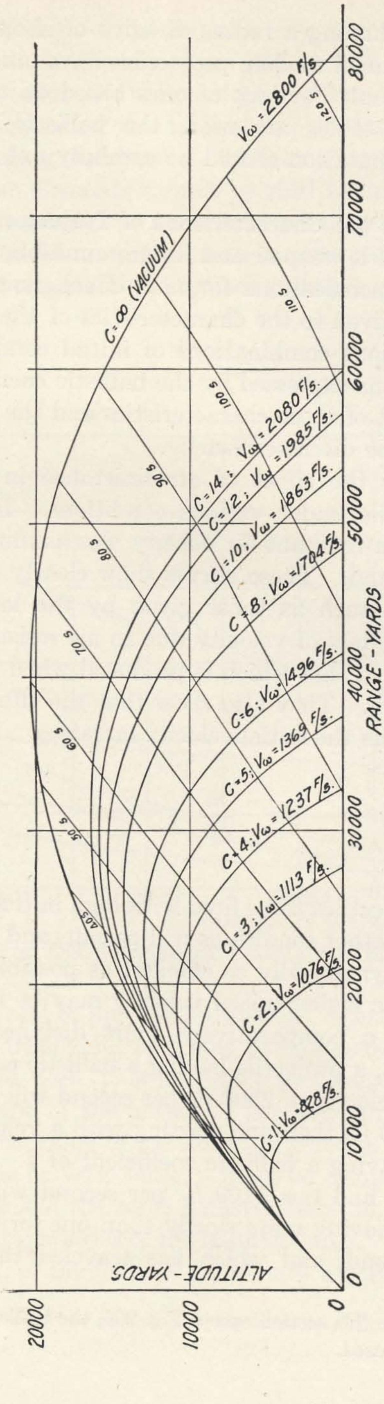


FIG. 239.—Plots of Trajectories (v_0 = 2800 ft. per second, θ_0 = 45°).

Figure 239 is a plot of a sheaf of trajectories with $v_0 = 2800$, $\theta_0 = 45°$, and with various values of C_J. The great reduction in range for small values of C_J compared with that obtained in vacuo with $C = \infty$, should be noted.

In antiaircraft fire a short time of flight is of great value. Figure 240 shows that raising the initial velocity is the most effective way of shortening the time of flight. It also shows, however, that at the high initial velocities the efficiency of the projectile, as expressed by its ballistic coefficient, is of almost equal importance.

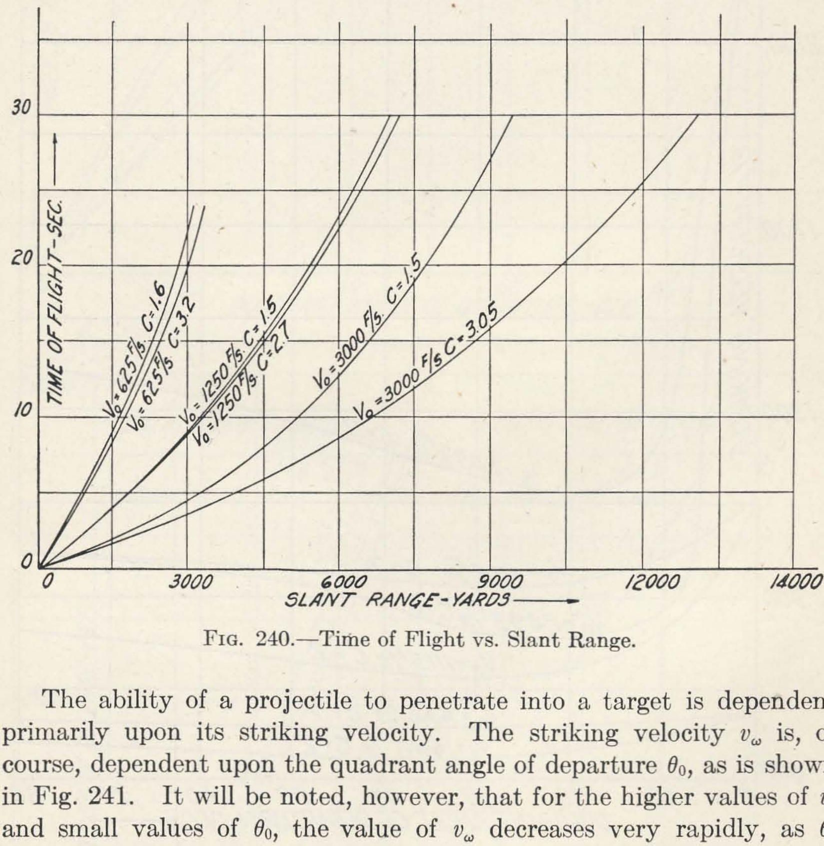


FIG. 240.—Time of Flight vs. Slant Range.

The ability of a projectile to penetrate into a target is dependent primarily upon its striking velocity. The striking velocity v_ω is, of course, dependent upon the quadrant angle of departure θ_0, as is shown in Fig. 241. It will be noted, however, that for the higher values of v_0 and small values of θ_0, the value of v_ω decreases very rapidly, as θ_0 increases; especially if the value of C is low.

When firing against targets on reverse slopes, and when firing high explosive shell for fragmentation effect against targets on the ground, a high angle of fall is very desirable. The angle of fall is determined principally by the angle of departure, being always greater than the latter for ballistic table conditions, as is shown in Fig. 242.

The dropping of bombs from aircraft in horizontal flight presents a special range of conditions. The quadrant angle of departure is always as nearly zero as the pilot can make it. The initial velocity of the bomb is the speed of the aircraft at the instant the bomb is released. It is

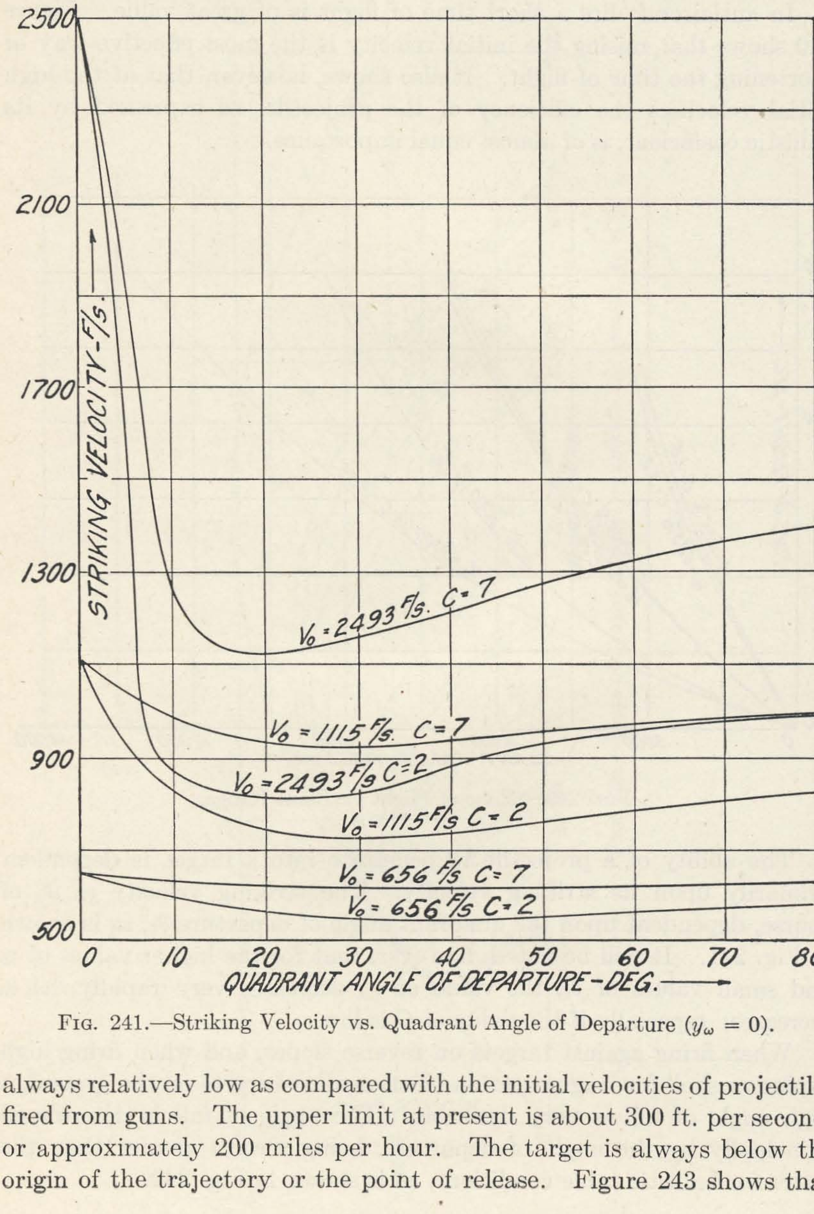


FIG. 241.—Striking Velocity vs. Quadrant Angle of Departure ($y_\omega = 0$).

always relatively low as compared with the initial velocities of projectiles fired from guns. The upper limit at present is about 300 ft. per second, or approximately 200 miles per hour. The target is always below the origin of the trajectory or the point of release. Figure 243 shows that

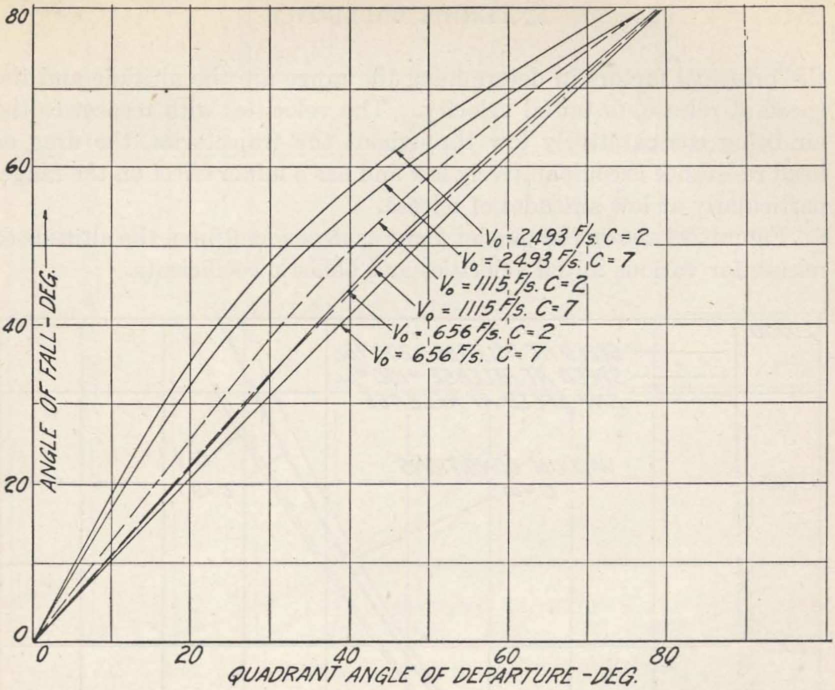


FIG. 242.—Angle of Fall vs. Quadrant Angle of Departure ($y_\omega = 0$).

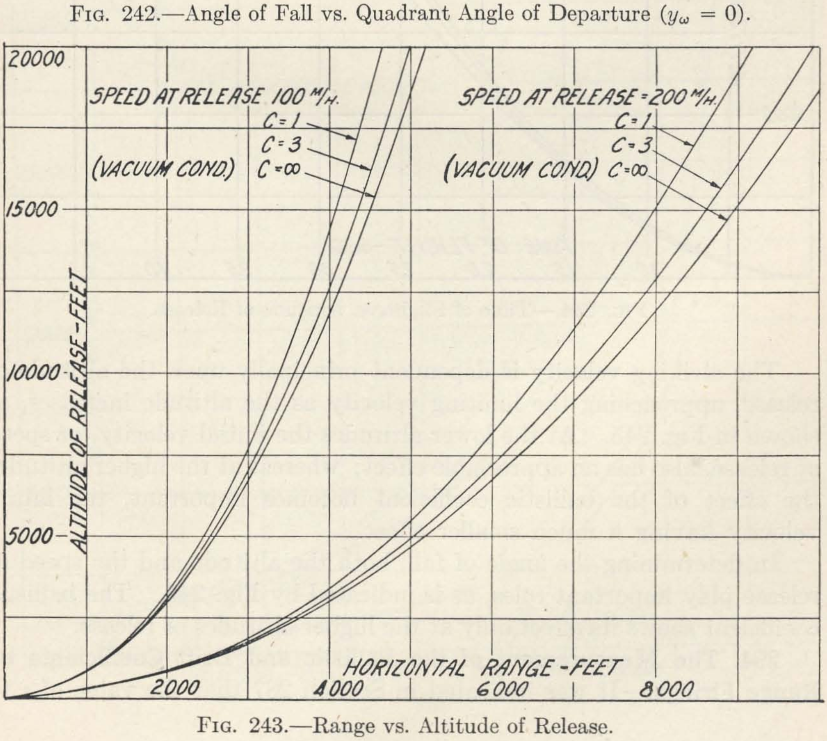


FIG. 243.—Range vs. Altitude of Release.

the principal factors in determining the range are the altitude and the speed at release, or initial velocity. The velocities with respect to the air being comparatively low throughout the trajectories, the drag or head resistance is comparatively low and has a minor effect on the range, particularly at low altitudes of release.

Figure 244 shows the time of flight as dependent upon the altitude of release for various initial velocities and ballistic coefficients.

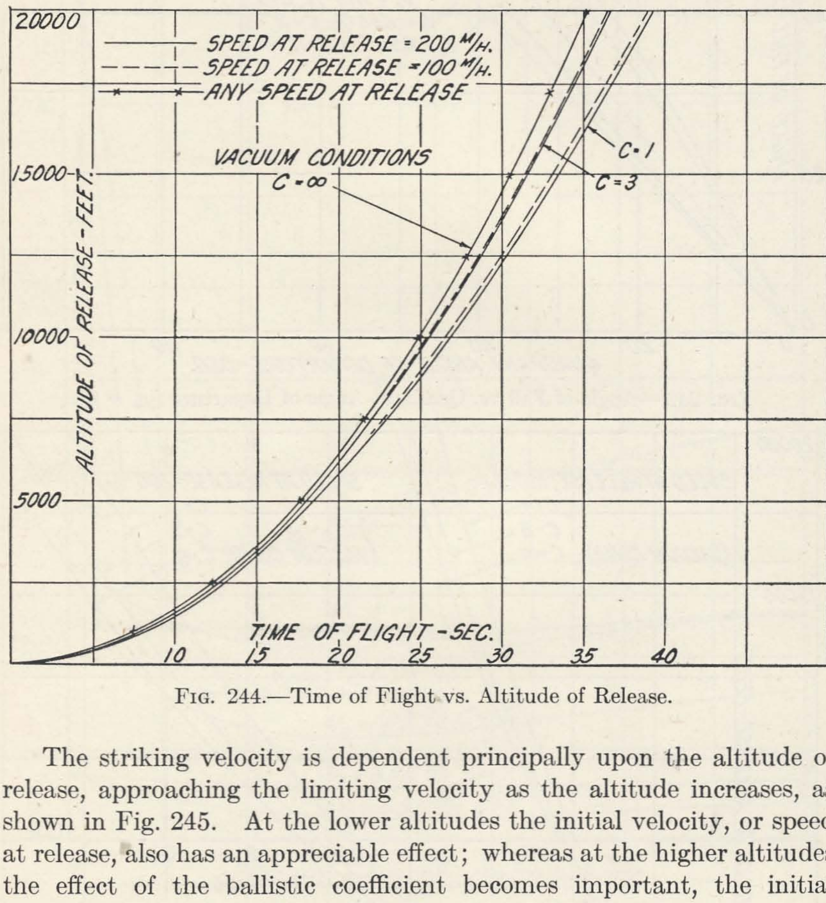


FIG. 244.—Time of Flight vs. Altitude of Release.

The striking velocity is dependent principally upon the altitude of release, approaching the limiting velocity as the altitude increases, as shown in Fig. 245. At the lower altitudes the initial velocity, or speed at release, also has an appreciable effect; whereas at the higher altitudes the effect of the ballistic coefficient becomes important, the initial velocity having a much smaller effect.

In determining the angle of fall, both the altitude and the speed of release play important roles, as is indicated by Fig. 246. The ballistic coefficient shows its effect only at the higher altitudes of release.

294. The Measurement of the Ballistic and Drift Coefficients by Range Firings.—It was indicated in Section 287 that the value of i to

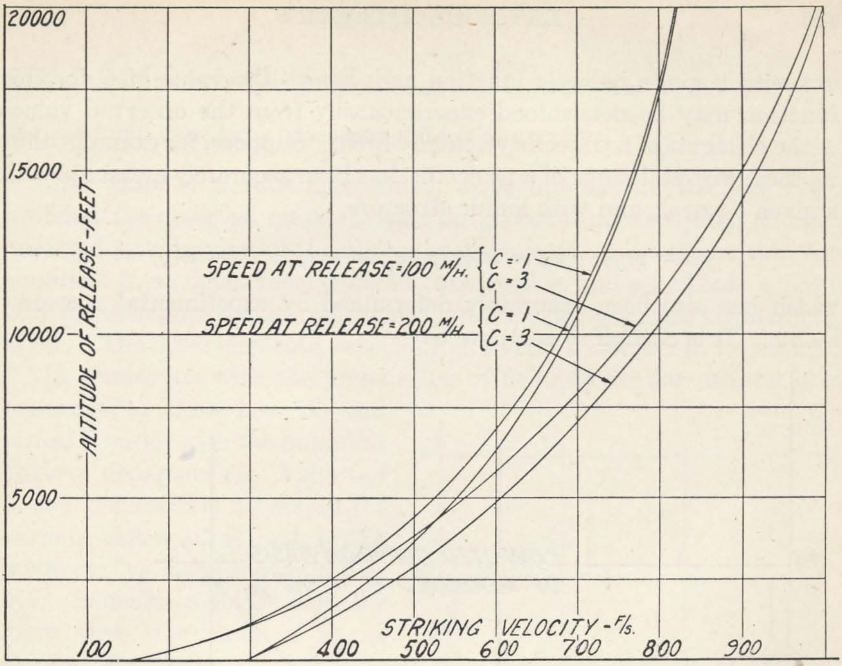


FIG. 245.—Striking Velocity vs. Altitude of Release.

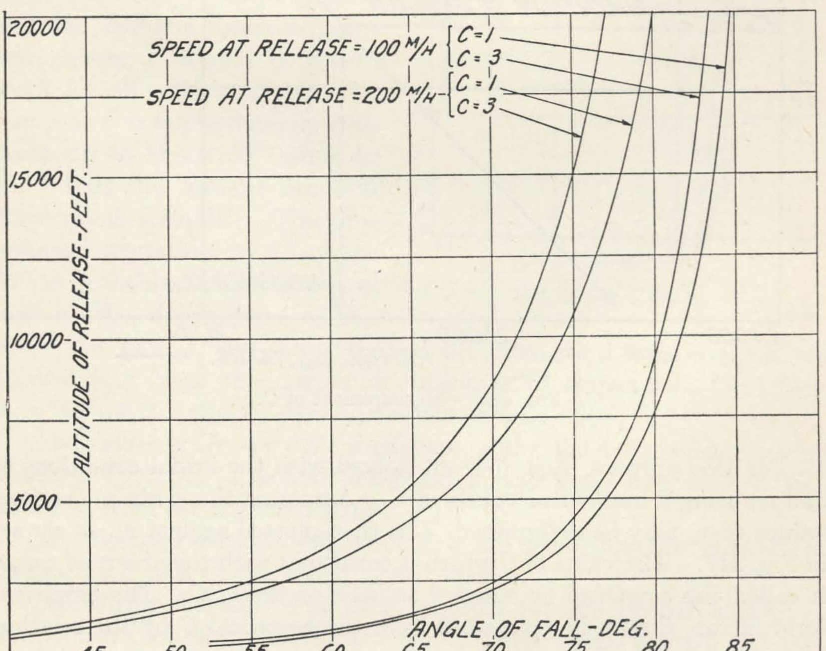


FIG. 246.—Angle of Fall vs. Altitude of Release.

use with a given ballistic function and, hence, the value of C for this function may be determined experimentally from the observed values of the elements of a trajectory actually fired. Suppose, for example, that x_ω, the horizontal range of a projectile, has been accurately measured with a given θ_0, v_0, y_ω and with an air structure,

$$\rho = \rho(y), \quad w_x = w_x(y), \quad w_z = w_z(y), \quad a = a(y)$$

which has also been accurately determined by experimental measurements. It is desired to compute C.

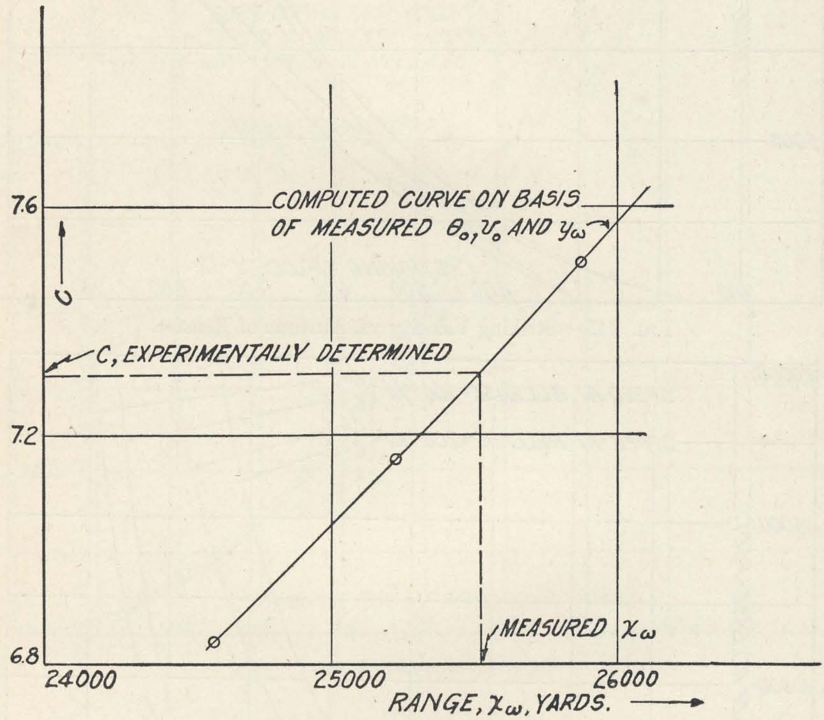


FIG. 247.—Measurement of C.

For this purpose, Eqs. (14) are solved with the initial conditions θ_0 and v_0, using a number of values of C. Assuming the given y_ω, various values of x_ω may be determined. C is then plotted against x_ω, as shown in Fig. 247. The value of C which is consistent with the observed range is called the *empirical* or *observed ballistic coefficient* C. The empirical form factor, i, may be computed from the empirical C by the relation $C = \frac{m}{id^2}$. This form factor may be used for other projectiles of the

same shape, launched with approximately the same initial conditions, if the sectional density, $\frac{m}{d^2}$ does not differ too greatly.

The value of C thus determined, when inserted in the Eqs. (14), produces the observed range x_ω, with the given initial conditions and the observed y_ω. In view of the approximations used, it is evident that the empirical C, as determined from the observed x_ω and y_ω, affords a basis only for the approximate computation of the other terminal elements t_ω, ω, etc. The other elements, especially t_ω, should be measured if possible.

In connection with the preparation of firing tables for cannon it is necessary to know how the empirical C varies with the quadrant angle of departure θ_0. Values of C are determined as stated for various values of θ_0 and a plot made of C vs. θ_0, as shown in Fig. 248. Sometimes this is done for more than one value of v_0, as shown.

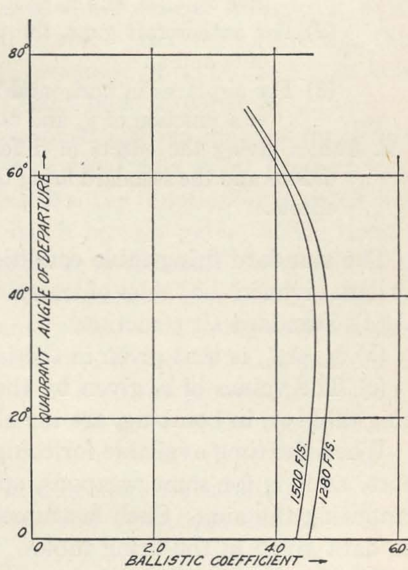


FIG. 248.—C vs. θ_0.

If the theory were adequate and the ballistic function properly chosen, C should be a constant for all values of θ_0. The fact that C is approximately constant up to about 50° tends to show that the ballistic function chosen was suitable. The pronounced variation in C above 50° is probably due to the neglect of the dependence of K_D upon the yaw δ, and the neglect of the cross wind force components L_x and L_y. Near the maximum ordinates of trajectories for which $\theta_0 > 40°$, δ, L_x, and L_y should be appreciable.

The values of C_L, the drift coefficient, and j, the drift factor, may be obtained from the observed deflection in the same way that C was obtained from the observed range.

The firings mentioned above which are made for the purpose of measuring C and C_L are called *Range Firings*.

295. Firing Tables.—The data required for the proper aiming of weapons are contained in *Firing Tables*. These tables contain the data from which the proper pointing of a particular weapon firing a particular kind of ammunition may be deduced or computed, as depending upon

the coordinates x, y, and z of the target, and the air structure holding at the time of firing.

Although they differ greatly in content and form, firing tables generally contain:

a. The characteristics of the weapon and the ammunition pertaining to it.

b. Tables of general data required or useful in the direction and adjustment of fire.

c. Tables of trajectory data or elements, under firing table conditions. For example,

(1) For cannon firing on targets at nearly the same level, the tables give θ_0, t_ω, ω, and z_ω as functions of x_ω.

(2) For antiaircraft guns, the tables give x_ω, y_ω, and z_ω as functions of θ_0 and t_ω.

(3) For airplanes in horizontal flight, θ_0 being zero, the tables give x_ω as a function of y_ω and v_0.

d. Tables giving the effects of differences between the actual firing conditions and the standard firing table conditions, often called differential effects.

The standard firing-table conditions assumed in the computation of the data given in the tables of trajectory data are usually as follows:

(*a*) Standard air structure.

(*b*) y_ω or t_ω is that given in the table.

(*c*) The values of v_0 given by the weapon are those specified in the firing table or, in bombing, are the air speeds of the plane.

When the time available for computing the elevation and azimuth is short, as it is for some weapons, special instruments are provided for computing the aim. Such instruments are constructed on the basis of the data given in the firing tables.

The firing tables themselves are based on trajectories computed with ballistic coefficients determined from range firings as explained in Section 294.

In tabulating the elevations and azimuths required to obtain a given range and deflection from a gun, account is taken of the fact that usually the direction of the tangent to the trajectory at the origin differs from that of the axis of the bore of the gun before the gun is fired. This difference in direction is called *jump*, and is determined experimentally in the range firings.

296. Differential Effects.—Certain firing-table conditions are assumed in computing firing tables. In the field, the actual conditions of firing usually differ from those of the firing tables. The differences due to the variations of the actual conditions from the firing-table conditions are called the differential effects. In the following, the condi-

tions which differ from firing-table conditions will be referred to as non-standard.

The standard conditions are of several types. These include conditions which are the same for all firings, such as standard air structure; conditions standard for a particular gun, such as service velocity; and, finally, some condition arbitrarily assumed as standard merely for a point of departure, such as a particular quadrant elevation. A non-standard condition generally has an effect upon the whole trajectory. The particular form in which the effect is recorded differs according to the class of trajectory. Thus, in ground fire, the only effect recorded is usually that on range, and this means range on the level, that is, the change in x_ω when y_ω remains equal to zero. Accompanying this there is, of course, a change in t_ω, but this is usually of no interest. In bomb trajectories, however, the effect on t_ω may be of importance.

The two types of trajectories mentioned agree in that the functioning of the projectile is determined by its arrival at a point where y has a certain value. In antiaircraft projectiles, the functioning is determined by the arrival at a point where t has a certain value, which depends upon the fuze setting. Consequently, in antiaircraft firing tables, the effect on horizontal range of any non-standard condition means the change in x_ω when t_ω remains constant. There is also regularly recorded the change in y_ω for the same condition. It should be clear from the foregoing that, even if the same gun is used for ground fire and antiaircraft fire, and even if the burst is on the ground, the recorded effect on horizontal range of any non-standard condition will be quite different in an antiaircraft table from that in a ground-fire table.

The following variations from standard conditions and their effects on range are considered:

- Variation in v_0 from standard.
- Variation in quadrant angle of departure θ_0.
- Variation in the altitude of the point of fall from standard (height of site).
- Range component of the wind as a function of y.
- Variation in density from standard as a function of the altitude y.
- Variation in temperature from standard as a function of y (effect of temperature on velocity of sound, a).
- Variation in ballistic coefficient from standard.
- Variation in the mass of the projectile from standard.

An increase, Δm, in the mass m of the projectile influences the range in two different ways: (1) it reduces the muzzle velocity v_0; (2) it augments the ballistic coefficient C by an amount ΔC. From interior

ballistic data, the change Δv_0 in v_0 is ascertained. The range effect $\Delta_m x$ is obviously given by

$$\Delta_m x = \Delta_v x - \Delta_C x$$

In this equation, $\Delta_v x$ and $\Delta_C x$ are the range effects corresponding to the velocity and ballistic coefficient changes produced by the given change Δm in m.

In addition to the differential effects in range, there is also considered a deflection effect, due to the cross wind, as a function of y. The range and deflection effects caused by the angular velocity of the earth Ψ should also be considered.

The range and deflection effects produced by the variations from firing-table conditions are given in the firing tables. Other effects, such as the time of flight, are sometimes also given. These will not be discussed here but they may be computed by methods similar to those used in computing the range and deflection effects.

The differential range effects are the differences between the ranges under standard conditions and the ranges with the given variations from standard conditions. The calculation of the range under standard conditions is accomplished by using Eqs. (15), with standard air structure. The range for the non-standard condition is computed by means of Eqs. (14), or by (15) if the non-standard condition assumes a standard air structure. The difference between the range calculated from the standard conditions and that obtained from the non-standard condition is the differential effect in range for the given non-standard condition.

Similar methods are used for calculating the differential effects in deflection. The following example will illustrate the method. Suppose it is desired to compute $\Delta_w x$, the range effect of a range wind,* $w_x = w_x(y)$, the air structure being considered standard except in regard to the range wind; that is, $w_y = w_z = 0$, $\rho = \rho_0 e^{-hy}$, and $a = a_0$.

Under these conditions,

$$u_x = v_x + w_x(y),\ u_y = v_y,\ u_z = v_z, \text{ and } u^2 = v_x^2 + v_y^2 + v_z^2 + w_x^2 + 2w_x v_x.$$

With these substitutions, Eqs. (14) become

$$\frac{dv_x}{dt} = -\frac{\rho_0 e^{-hy} F(u)\cdot(v_x + w_x)}{C}$$

$$\frac{dv_y}{dt} = -\frac{\rho_0 e^{-hy} F(u)\cdot v_y}{C} - g$$

$$\frac{dv_z}{dt} = -\frac{\rho_0 e^{-hy} F(u)\cdot v_z}{C} + \frac{Q(u)\cdot(v_x + w_x)}{C_L}.$$

* For brevity, the x component of the wind is called the range wind.

The difference between the range x computed from these equations with the given v_0, θ_0, and C, and that computed from Eqs. (15), is the required range effect $\Delta_w x$.

The range effect of a change in θ_0, the quadrant angle of departure, is computed not from calculated trajectories but directly from the angle of departure-range relation as given in the firing table. If firings at more than one initial velocity v_0 are available, the range effect of a change in v_0 should be based on the observed range difference corresponding to the velocity differences.

297. Ballistic Wind, Density, and Temperature.—The actual wind, density, and temperature are complicated functions of the altitude. Therefore, the meteorological station computes the ballistic wind, density, and temperature, the range effects of which are given in the firing table. Definitions of these terms follow.

The *ballistic range wind* is that constant wind w_x, independent of y, the range effect of which is equal to that of the observed range wind $w_x(y)$.

The *ballistic cross wind* is that constant cross wind w_z, the deflection effect of which is equal to that of the observed cross wind $w_z\ (y)$.

The *ballistic density* is that density, the ratio of which to $\rho_0 e^{-hy}$ is independent of y, and which produces the same range as the observed density $\rho(y)$.

The *ballistic temperature* T is that constant temperature which produces the same effect as the observed temperature $T(y)$.

Since the ballistic range wind is a sort of average or effective wind, it will be designated by $\overline{w}_x$. The range effect of a unit ballistic wind is represented by Δx, so that, assuming the range effect proportional to the wind, the range effect of a wind $\overline{w}_x$ is $\overline{w}_x \Delta x$.

The range effect of the ballistic wind may be calculated by the aid of Eqs. (14) and (15) for various values of $\overline{w}_x$. The results of these computations $\overline{w}_x \Delta x$, are tabulated in the firing table.

To discover what ballistic range wind $\overline{w}_x$ is equivalent to the observed range wind $w_x(y)$ is a more complicated matter. The wind is measured for a series of horizontal strata of the atmosphere up to the maximum ordinate. Let the range components of the winds in these strata, beginning at the stratum next to the ground, be designated by w_1, w_2, w_3, w_4 (assuming four strata). By $\Delta_1 x$, we represent the range effect for a given trajectory of a unit range wind in the first stratum, the other w's being zero. $\Delta_2 x$, $\Delta_3 x$, and $\Delta_4 x$ are defined in a similar manner. It is now assumed that the range effect of the wind in each stratum is directly proportional to the wind velocity in the given stratum. On the further assumption that the net effect of the winds w_1, w_2, w_3, and w_4

is the sum of their individual effects, it is evident from the definition of the ballistic range wind $\overline{w}_x$ that

$$\overline{w}_x \cdot \Delta x = w_1 \cdot \Delta_1 x + w_2 \cdot \Delta_2 x + w_3 \cdot \Delta_3 x + w_4 \cdot \Delta_4 x.$$

Upon dividing through by Δx and replacing $\frac{\Delta_1 x}{\Delta x}$ by q_1, $\frac{\Delta_2 x}{\Delta x}$ by q_2, etc., this becomes

$$\overline{w}_x = q_1 w_1 + q_2 w_2 + q_3 w_3 + q_4 w_4.$$

The q's are called the *range wind weighting factors.* It is clear that the q for any stratum is the ratio of the range effect of a unit range wind in that stratum to the range effect of a unit range wind blowing in all four strata. By the aid of the range wind weighting factors, the meteorological station computes the ballistic range wind $\overline{w}_x$ for various representative trajectories.

Similar methods may be used for computing the ballistic density $\overline{\rho}$, the ballistic temperature $\overline{T}$, and the ballistic cross wind $\overline{w}_z$.

During the World War various nations began the practice of calculating ballistic winds, densities, and temperatures by the aid of weighting factors. The method of computing the differential effects and weighting factors described above has not been much used in this country until recently. The procedure more generally followed was devised by Bliss and Gronwall.

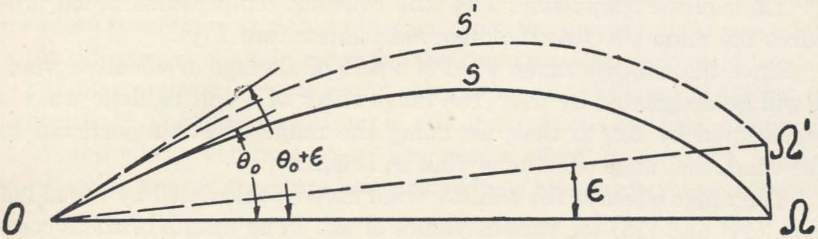


FIG. 249.—Illustrating the Rigidity of the Trajectory.

298. The Rigidity of the Trajectory.—Among the differential effects in range, there has been mentioned that corresponding to the variation in the height of site from normal. The negative of the range change corresponding to the increase in θ_0 required to *correct for the height of site* is the height of site effect which is given in the range tables. For small arms and field artillery it is sometimes desirable to employ a more rapid method of correcting for the height of site than by using the height of site effect given in the firing tables. In such cases, a procedure based on the principle of the rigidity of the trajectory may be used. This principle may be stated with the aid of Fig. 249, which shows a trajectory

$OS\Omega$ with the origin and the point of fall connected by a line $O\Omega$. Let the angle of site be augmented from zero to ϵ. Then, if the quadrant angle of departure θ_0 is raised to $\theta_0 + \epsilon$, the shape and dimensions of the resulting figures $OS'\Omega'$ are approximately the same as those of $OS\Omega$, for small values of ϵ.

To prove this theorem, the equations of motion will be considered for the case that the OX axis makes an angle ϵ with the horizontal, as shown in Fig. 250. Neglect the motion in z and therefore L_z. The components of the drag D are D_x and D_y, and those of the weight are $-mg \sin \epsilon$ and $-mg \cos \epsilon$. If ϵ is small, the difference between $\cos \epsilon$ and 1 may be neglected, and then the components of the weight are $-mg \sin \epsilon$ and $-mg$. The components D_x and D_y are evaluated by the method of Section 286. If these results are incorporated in the equations of motion, Eqs. (14) become:

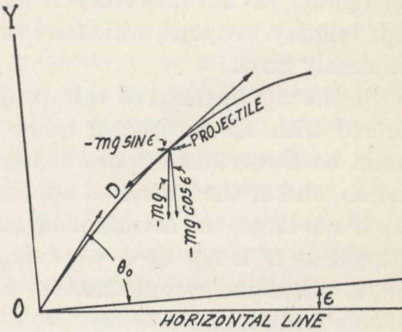


FIG. 250.—X Axis Inclined to the Horizontal.

$$\frac{dv_x}{dt} = -\frac{\rho \cdot F \cdot u_x}{C} - g \sin \epsilon = -\frac{\rho \cdot F \cdot u_x}{C}\left(1 + \frac{Cg \sin \epsilon}{\rho F \cdot u_x}\right) \tag{19}$$

$$\frac{dv_y}{dt} = -\frac{\rho \cdot F \cdot u_y}{C} - g$$

Since the axes are inclined, ρ is no longer a function of y only, but of the altitude, $(y \cos \epsilon + x \sin \epsilon)$, which is approximately equal to $(y + x \sin \epsilon)$. In other words, $\rho = \rho(y + x \sin \epsilon)$.

It is apparent from Eqs. (19) and the expression $\rho = \rho(y + x \sin \epsilon)$ that if, for all parts of the trajectory,

$$\frac{Cg \cdot \sin \epsilon}{\rho F \cdot u_x} \tag{20}$$

is small compared to unity, and the change in density due to the change in altitude $x \sin \epsilon$ is small, then Eqs. (19) are independent of ϵ.

If θ_0 be taken as the superelevation and kept constant as ϵ is changed, the initial conditions are also independent of ϵ. From this it follows that the trajectory referred to the tilted axes is approximately independent of ϵ under the conditions given, or that the trajectory is approximately rigid.

It is evident that a small value of C and large values of u and u_x tend to make the value of expression (20) small. A small value of C will, in general, make the range x_ω small, and thus the change in density due to $x \sin \epsilon$ will be relatively small. From this, it follows that the principle of the rigidity of the trajectory is most nearly correct for small caliber, high velocity weapons, which are the very weapons for which it is most frequently used.

In the application of this principle, the firing tables arė usually entered with the horizontal range instead of the slant range $O\Omega'$, as would be theoretically more nearly correct. Because of this approximation, and of the restricted applicability of the principle itself, especially if ϵ is large, the actual quadrant angle of departure required to hit a target at Ω' is not $\theta_0 + \epsilon$, as shown in Fig. 249, but $\theta_0 + \epsilon + \Delta_\epsilon\theta_0$. $\Delta_\epsilon\theta_0$ is called the complementary angle of site correction and is given in some firing tables.

299. The Rotation of the Earth.*—It was pointed out in Section 277 that the differential equations of a trajectory as derived there are based on the assumption that the earth is motionless. This hypothesis, of course, is not correct; but it is only in the longest trajectories that the resulting error is significant. It was shown by Poisson in 1838 and by Moulton in 1918 that, if the differential equations derived on the assumption of no rotation are

$$\frac{dv_x}{dt} = E_x, \quad \frac{dv_y}{dt} = E_y, \quad \text{and } \frac{dv_z}{dt} = E_z \tag{18}$$

then the equations which take account of the earth's rotation are

$$\begin{aligned} \frac{dv_x}{dt} &= E_x - 2\Psi v_y \sin \alpha \cdot \cos L \\ \frac{dv_y}{dt} &= E_y + 2\Psi v_x \sin \alpha \cdot \cos L \\ \frac{dv_z}{dt} &= E_z + 2\Psi(v_x \sin L - v_y \cos \alpha \cdot \cos L) \end{aligned} \tag{21}$$

where Ψ is the earth's angular velocity in radians per second, L is the latitude, and α is the azimuth of fire reckoned from the north.

As in other differential effects, the range and deflection in a solution

* The first treatment of this subject is contained in La Place's "Mécanique Céleste."

of Eqs. (21) may be compared with those in the corresponding solution of Eqs. (18), and thus the effect of the rotation on range and deflection for any specified values of α and L may be determined. Certain peculiarities, however, present themselves here. For any other non-standard condition, the non-standard condition may conceivably, or even actually, be absent. For example, an absolutely windless day may be very unlikely; but it is possible. There is, however, no prospect of firing a gun with the earth motionless, and it is not even possible to select L and α so that all the corrective terms vanish at once. This implies that when the effect of rotation is not negligible, there is no condition whatever in which the solution of Eqs. (18) will give the correct point of fall. Nevertheless, the solution is taken as standard, as it constitutes by far the best point of departure from which to reckon the effects of rotation for different latitudes and azimuths. That is, for a given muzzle velocity, angle of departure, and ballistic coefficient, the various points of fall for different values of L and α are symmetrically distributed around the point of fall given by the solution of Eqs. (18).

Another peculiarity of this problem is the presence of two variable parameters, L and α. This would make prohibitive the labor of computing the effects of all possible combinations of these. On the other hand, the effect is always relatively small, and it is never more than 1 per cent in range or 10 mils in deflection. For this reason, it may be assumed that the effect is proportional to the magnitude of the term representing the disturbing cause. Since the range effect is computed by means of the first two of both Eqs. (18) and (21) on this assumption, the range effect may be written as $A \sin \alpha \cos L$, and the value of A determined by computation for a case where the product, $\sin \alpha \cos L$, does not vanish, such as $\alpha = 90°$, $L = 0$. Likewise, on the assumption of proportionality of effect to the magnitude of the term involved, the deflection effect, involving the third of both Eqs. (18) and (21), may be written as $B \sin L - D \cos \alpha \cos L$. If $L = 90°$ and $\alpha = 90°$, the term in D vanishes and B may be computed. If $\alpha = 0$ and $L = 0$, the term in B vanishes and D may be computed. It is readily seen, therefore, that the determination of the three quantities, A, B, and D, is sufficient for finding the effect of rotation for any latitude and azimuth of fire.

The general character of the displacement of the point of fall is not evident from the differential equations. The following discussion is an attempt to explain the phenomenon in more elementary terms. In the first place, it is well known that, if an object is viewed by an observer having a certain motion, the object will have with reference to the observer an equal and opposite motion in addition to its own

motion with reference to a fixed system. This applies to angular motion as well as linear, and accounts for the principal part of the apparent motion of the sun, moon, and stars. With reference to an observer on the earth, they rotate from east to west about an axis because the observer is carried with the earth from west to east about this axis. In precisely the same way, a projectile during its time of flight, has, with reference to the earth or an observer on it, an angular motion equal and opposite to that of the earth. Thus, if a projectile is fired toward the azimuth of a star at the instant that the star appears on the horizon, then, at the end of the time of flight, computed for a motionless earth, the projectile instead of reaching the ground will have an azimuth and angle of site equal respectively to those of the star. Thus, for example, a projectile fired eastward at the equator will have its trajectory raised and, consequently, the range increased.

The effect just described is the principal one except for very long times of flight. In this case another phenomenon predominates. In the ordinary computation of a trajectory it is assumed that gravity acts in a constant direction parallel to that called vertical at the point of departure. Actually, the direction converges toward the center of the earth and, hence, has a horizontal component tending to draw the projectile *backward* toward the point of departure. Now, since the rotation of the earth carries the projectile eastward, this horizontal component introduces a westward force not provided for in the original computation. Consequently, besides the previously described displacement due solely to the motion of the reference system, there is a further displacement actually carrying the projectile to the west of where it would otherwise be at a given instant.

300. Comparison of Observed and Computed Differential Effects.— At the Proving Ground, two 75-mm. Guns, Model 1897, carefully calibrated with respect to each other, were placed about 10 miles apart and fired toward each other at the same quadrant angle of departure. The firings were repeated on other days. After allowance was made for the difference in muzzle velocity v_0, the remaining difference in range of the guns was twice the actual wind range change and the difference in deflection was twice the actual deflection change. These observed or measured wind effects were compared with those calculated using $F_G(u)$, which is approximately applicable to the short-pointed, flat-based projectile fired. The comparison is given below.

Observed and Computed Range and Deflection Effects for a 10 ft. per second Range or Cross Wind

$$\begin{bmatrix} v_0 = 1745 \text{ ft. per second} \\ \theta_0 = 42^\circ\, 30' \\ C_G = 1.377 \end{bmatrix}$$

	Range Effects Yards	Deflection Effects Mils
Observed Effect	12.56	0.945
Computed Effect	13.41	0.929
Difference	0.85	0.016
Prob. Error of Observed Effect	0.40	0.030

On the whole, the agreement is quite as good as could be expected.

This result and the fact that, as mentioned in Section 291, a single value of the form factor, i_J, was sufficient to account so accurately for the observed ranges of a projectile fired on four different days at two different elevations, tend to show that, when the *resistance function is suitable* and the *curvature of the trajectory not too great*, the theoretically calculated differential effects are in substantial agreement with the observed ones. This is of great importance so far as the practical utility of exterior ballistics is concerned, since the calculated differential effects are used on the field of battle to allow for the difference between the actual conditions and firing-table conditions.

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CHAPTER XI

PROBABILITY OF HITTING

When a great many shots are fired under conditions of laying and atmosphere as nearly identical as possible, it will be found that the shots have not fallen on the same spot but are grouped around a point. This is due, as a rule, chiefly to variations in the initial yaw and in the initial velocity. The scattering of shots due to these unavoidable variations is known as dispersion. Because of dispersion it follows that, unless the target is large, only a fraction of the shots will hit it. Because of the resulting uncertainty of hitting the target, it is desirable to devise a method for estimating the probability or likelihood of hitting a target of given dimensions, as dependent upon the laying of the piece and the dispersion characteristics of the gun or battery. The theory by which the probability is estimated is called the *theory of the probability of hitting.*

In order that effective, sustained fire may be delivered on a target without the expenditure of an excessive amount of ammunition, there must be accurate and continuous *observation of fire.* The practical procedure whereby the true center of impact of the observed shots is placed on the center of the target, and the maximum probability of hitting obtained, is called *adjustment of fire.* The methods of observation, and of the subsequent adjustment, are not discussed in this chapter; these subjects are tactical in nature, and pertain to practical gunnery.

In the following treatment of the theory of the probability of hitting, the terminology employed and the illustrations will be directly applicable to gun fire. However, most of the theorems, if not all, are also applicable to bombing from airplanes.

301. Definitions and Coordinates.—

TERM	SYMBOL	DEFINITION
Center of impact	C.I.	The center of gravity of the points of fall of a large number of rounds fired with a given laying of the piece.
Center of impact	c.i.	As above except that the number of rounds is small.
Target error of a round		Distance from the target to the point of impact of a given round.
Accidental error of a round		Distance from the C. I. to the point of fall of a given round.

Term	Symbol	Definition
Determinate error of the piece		Distance from the C.I. to the target.
Range accidental error *	x	Component of accidental error along the X axis.
Deflection accidental error *	z	Component of accidental error along the Z axis.
Range determinate error	x_T	Component of determinate error along the X axis.
Deflection determinate error	z_T	Component of determinate error along the Z axis.
Range target error	$(x - x_T)$	Component of target error along the X axis.
Deflection target error	$(z - z_T)$	Component of target error along the Z axis.

* Because of their frequent use, the terms *range accidental error* and *deflection accidental error* will be shortened to *range error* and *deflection error*.

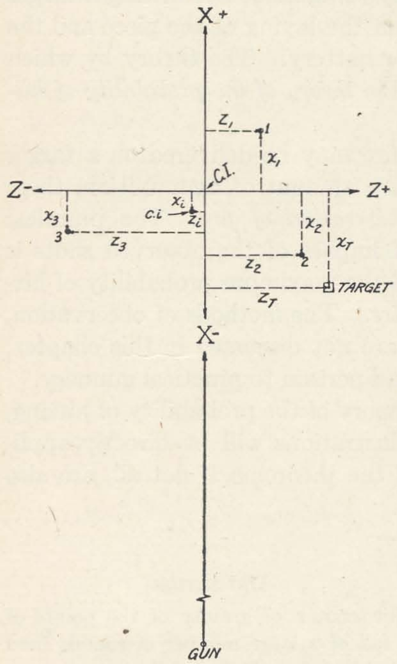

FIG. 251.—Coordinate System.

Coordinates.—A system of rectangular coordinates is adopted, with the origin at the C.I., and with the axes in the horizontal plane of the target. (Fig. 251). The X axis lies in the vertical plane through the gun and the C.I., and the Z axis is perpendicular to it.

If the rounds fired with a given laying of the gun are numbered 1, 2, 3, . . . n, the coordinates of the k^{th} round are x_k, z_k, and these are the range and deflection errors of the point of impact. The coordinates of the c.i. of n rounds are x_i, z_i, and of the center of the target, x_T, z_T.

302. Probability.—If a very large number of rounds n have been fired at a target with a given laying of the piece and unchanging weather conditions, and of these n_h hit, then we define the *probability* p of hitting for an additional round under the same conditions by

$$p = \frac{n_h}{n}.$$

Obviously, n_h cannot be greater than n. Thus the maximum possible value of p is unity, which is equivalent to certainty.

In attacking a given target, there will not have been fired previously a very large number of rounds, and thus there is no direct method for determining the probability of hitting. On the other hand, in range firing at the proving ground a considerable number of rounds will have been fired and their points of fall plotted. From the results of these firings and from certain assumptions to be explained later, it is possible to make an estimate of the probability p.

303. Probable Error.—Let it be supposed that a large number of shots have been fired, the points of impact plotted as in Fig. 252, and the C.I. located. Assuming symmetrical distribution of these points with reference to the axes, two lines, of which the equations are $x = \epsilon_x$ and $x = -\epsilon_x$, are drawn parallel to the Z axis. If the value of ϵ_x is chosen so that half the total number of shots lies between the two lines, this value, ϵ_x, is the *range probable error*. It is equal to half the depth of the zone measured along the X axis in which 50 per cent of the shots have fallen.

Similarly, if two lines are drawn parallel to and equidistant from the X axis, so as to include one half the total number of shots, the *deflection probable error* ϵ_z is equal to half the distance between them, or half the width of the zone measured along the Z axis in which 50 per cent of the shots fell.

From the foregoing, it is apparent that the chances are even that the range error of a single shot or point of impact will be numerically less than ϵ_x. Similarly, considering deflection only, the chances are even that the deflection error will be less than ϵ_z. Therefore, the probable error in range or in deflection (considered independently), is one that is just as likely to be exceeded as not.

304. The Probability Function and Integral.—It has been found from a large number of tests that, with occasional exceptions, the probability, $p_{x_{1,2}}$, that the range error of a shot will fall between the limits x_1 and x_2 may be represented approximately by

$$\frac{h}{\sqrt{\pi}}\int_{x_1}^{x_2} e^{-h^2x^2}\,dx.$$

In this expression, h is called the *modulus of precision*, and e is the base of the Napierian logarithmic system. It may be shown that h is equal to $\frac{k}{\epsilon_x}$, where ϵ_x is the range probable error and k is a number which is approximately equal to 0.477.

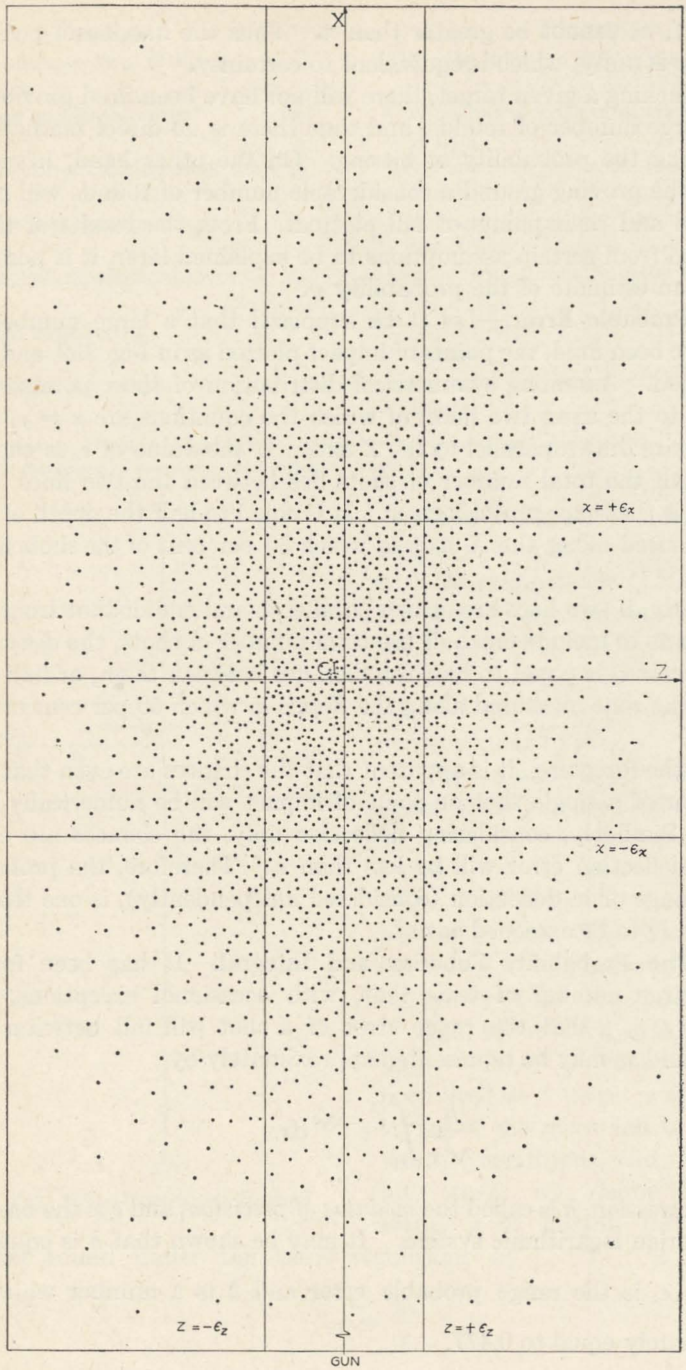

FIG. 252.—Illustrating Probable Error.

This expression for the probability $p_{x_{1,2}}$ has been deduced theoretically on certain plausible assumptions. It is used in this treatment because its properties are known and because it is at least approximately in accordance with the experimental results. If the distribution of the shots is such that the probability that the x coordinate of a shot will lie between x_1 and x_2 is accurately given by the above expression, the distribution of the points of impact is said to be normal. In the following, it will be assumed that the points of impact have a normal distribution both in range and deflection. The function $\frac{h}{\sqrt{\pi}} e^{-h^2x^2}$ is called the (normal) probability function. It is plotted in Fig. 253.

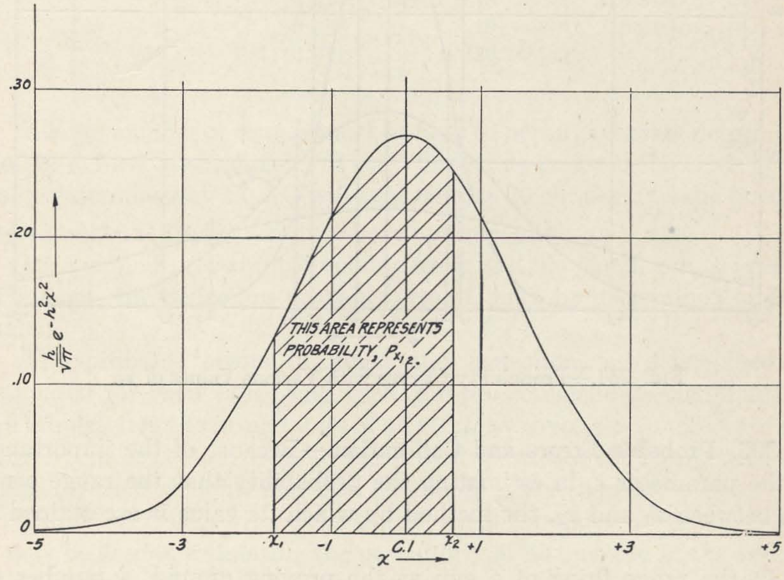

FIG. 253.—Plot of $\frac{h}{\sqrt{\pi}} e^{-h^2x^2}$ vs. x.

An infinity of curves could be obtained by varying ϵ_x and, accordingly, h. For the particular curve shown, $h = k = 0.477$, which is equivalent to taking $\epsilon_x = 1$. Since the definite integral of a function between two limits is equivalent to the area under the curve representing the function between the same limits, the shaded area represents the probability $p_{x_{1,2}}$ for the values of x_1 and x_2 shown, when $\epsilon_x = 1$.

To illustrate the way in which the shape of the curve changes as ϵ_x varies, a series of curves with various values of ϵ_x is shown in Fig. 254. It will be seen that with two given limits, x_1 and x_2, which bracket the

C.I., the probability of hitting is augmented as ϵ_x diminishes. On the other hand, if two limits x_3 and x_4 are chosen which do not bracket the C.I., the probability of hitting will, in many instances, diminish as ϵ_x diminishes.

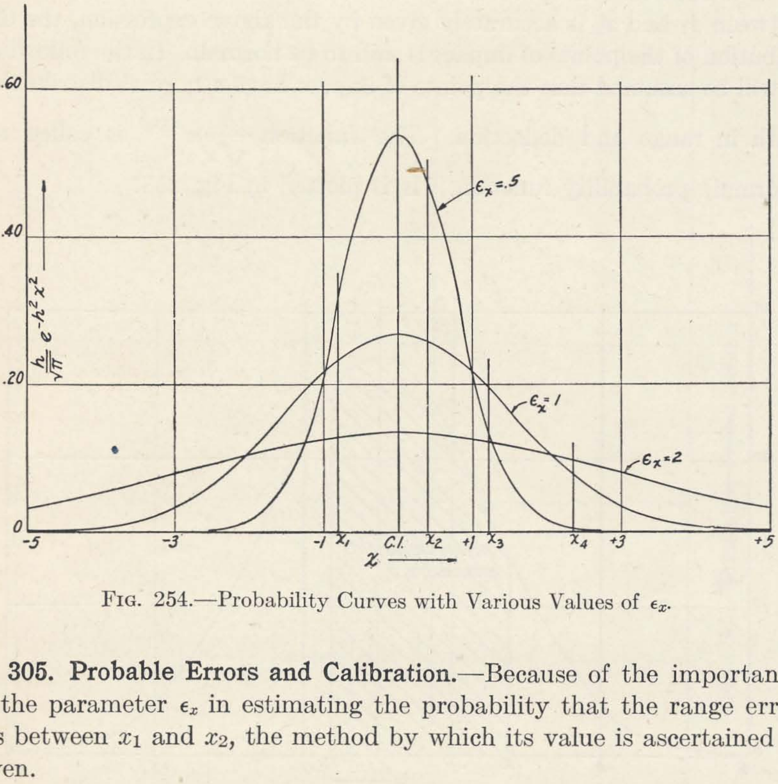

FIG. 254.—Probability Curves with Various Values of ϵ_x.

305. Probable Errors and Calibration.—Because of the importance of the parameter ϵ_x in estimating the probability that the range error lies between x_1 and x_2, the method by which its value is ascertained is given.

In the range firing of a gun at the proving ground, a number of rounds n are fired with the same laying of the piece and the locations of the points of impact are measured and plotted. Using the coordinate system of Fig. 251, the coordinates of the c.i. (small number of rounds) are x_i, z_i; the deviations of the rounds along the two axes, with respect to the c.i., are $v_{x_1}, v_{x_2} \cdots v_{x_n}$ and $v_{z_1}, v_{z_2} \cdots v_{z_n}$, so that $v_{x_1} = x_1 - x_i$, $v_{z_1} = z_1 - z_i$, etc. Then the range probable error may be estimated by the relation

$$\epsilon_x = \frac{0.845 \sum_{k=1}^{k=n} v_{x_k}}{\sqrt{n(n-1)}} \text{ or, more accurately, } \epsilon_x = a_n \left(\frac{\sum_{k=1}^{k=n} v_{x_k}{}^2}{n} \right)^{\frac{1}{2}} \tag{1}$$

In Eq. (1), the values of a_n, as dependent upon the number of rounds n, are as follows:

No. rounds, n	Value of a_n	No. rounds, n	Value of a_n
2	1.195	11	0.725
3	0.932	12	0.720
4	0.845	13	0.717
5	0.802	14	0.714
		15	0.711
6	0.776	16	0.708
7	0.760	17	0.706
8	0.747	18	0.704
9	0.738	19	0.703
10	0.731	20	0.701

A large number of rounds must be fired to permit accurate determination of ϵ_x for a given range. If only 10 rounds be fired, the error in the value determined by Eq. (1) will approximate 20 per cent; as the number increases above 10, the error will vary approximately as $\sqrt{1/n}$.

By a similar procedure, involving firing and the plotting of the points of impact, the deflection probable error ϵ_z may be determined or estimated.

The probable errors in range and deflection, as determined or estimated for each range and each gun-projectile-charge combination, are tabulated in the firing tables of all service weapons as functions of the range. An inspection of these values will show that they vary with the range (or time of flight) and that ϵ_x is much larger than ϵ_z.

In service firings with a single gun, these tabulated values of ϵ_x and ϵ_z may be used in estimating the probability of hitting and in the adjustment of fire. In general, however, when a battery of several guns is fired, the C.I.'s of the individual guns will not coincide, because of differences in the conditions of the bores and in the action of the guns and mounts.

The C.I. of the battery is the center of gravity of the centers of impact of the individual guns, as illustrated in Fig. 255. The battery errors of a gun, that is, its errors with respect to the battery C.I., will be greater than those with respect to its own C.I. To reduce battery errors to a minimum, elevation and deflection corrections should be applied to each gun as required to make their C.I.'s coincide. The firing-table probable errors for a single gun are then applicable to the battery.

The estimation of the differences between the C.I. of the No. 1 gun of a battery and that of each of the other guns under the same conditions of laying, and the determination of the range and deflection corrections to be applied to obtain coincidence of the C.I.'s, is termed *calibration.* Adjustment of fire of a well-calibrated battery is a much simpler process than of one poorly calibrated. However, since perfect calibration would require, theoretically, an infinite number of rounds, the actual battery errors are somewhat greater than the errors of a single gun.

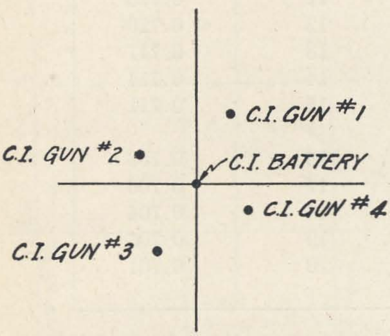

FIG. 255.—C.I. of Battery and of Individual Guns.

In a two-gun battery, with each gun firing n rounds for calibration, it may be shown that the *battery* range probable error is

$$\epsilon_x \cdot \sqrt{\frac{1}{2n} + 1}$$

ϵ_x being the probable error of a single gun. If firings are long continued after calibration, the centers of impact of the two guns will again begin to diverge because of differences in bore rate of wear, and the range probable error of the battery will be greater than that expressed above. If the battery consists of more than two guns, its probable error will, generally, be still greater. Calibration corrections are re-determined when the number of rounds fired and the results of firings warrant.

In the remainder of this discussion, ϵ_x will be used to designate the range probable error either of a single gun or of a calibrated battery as may be appropriate.

306. Evaluation of Probability Integral.—Since the probability $p_{x_{12}}$ that the range error of the point of impact lies between x_1 and x_2 is given by

$$\frac{h}{\sqrt{\pi}} \int_{x_1}^{x_2} e^{-h^2x^2} dx$$

it is desirable to develop an easy method for evaluating this integral. To facilitate the computations, a new variable, ξ, is introduced. Let $\xi = \dfrac{x}{\epsilon_x}$, so that $x = \epsilon_x \cdot \xi$ and $dx = \epsilon_x d\xi$. The quantity ξ is thus the ratio of the range error to the range probable error, or it expresses the magnitude of the range error in terms of the range probable error as the

unit of length. Upon substituting ξ for $\frac{x}{\epsilon_x}$ and replacing h by $\frac{k}{\epsilon_x}$, the integral is reduced to

$$\frac{k}{\sqrt{\pi}} \int_{\xi_1}^{\xi_2} e^{-k^2\xi^2} d\,\xi$$

where $\xi_1 = \frac{x_1}{\epsilon_x}$, $\xi_2 = \frac{x_2}{\epsilon_x}$, and, as before, $k = 0.477$.

To simplify evaluation of this expression, the integral $\frac{k}{\sqrt{\pi}} \int_0^{\xi} e^{-k^2\xi^2} d\xi$ is designated by $P(\xi)$ and tabulated as a function of ξ in Table I.

TABLE I

VALUES OF $P(\xi)$ FOR VARIOUS VALUES OF ξ

ξ	$P(\xi)$	ξ	$P(\xi)$
0.00	0.0000	2.50	0.4542
0.10	0.0269	2.60	0.4603
0.20	0.0537	2.70	0.4657
0.30	0.0802	2.80	0.4706
0.40	0.1064	2.90	0.4748
0.50	0.1321	3.00	0.4785
0.60	0.1572	3.10	0.4818
0.70	0.1816	3.20	0.4846
0.80	0.2053	3.30	0.4870
0.90	0.2281	3.40	0.4891
1.00	0.2500	3.50	0.4909
1.10	0.2709	3.60	0.4924
1.20	0.2903	3.70	0.4937
1.30	0.3097	3.80	0.4948
1.40	0.3275	3.90	0.4958
1.50	0.3442	4.00	0.4965
1.60	0.3598	4.20	0.4977
1.70	0.3742	4.40	0.4985
1.80	0.3876	4.60	0.4990
1.90	0.4000	4.80	0.4994
2.00	0.4114	5.00	0.4996
2.10	0.4217		
2.20	0.4311		
2.30	0.4396		
2.40	0.4473		

The values of ξ in column 1 are range errors varying in magnitude from 0 to +5 probable errors; the corresponding values of $P(\xi)$ in column 2 express the probabilities that these range errors will not be exceeded on any single shot. Also, since the number of shots that fall between two assigned limits 0 and ξ should bear the same ratio to the whole number of shots as $P(\xi)$ between these limits does to unity, any value of $P(\xi)$ gives the percentage of shots that may be expected to fall within ξ probable errors beyond the center of impact.

It is to be noted that $P(-\xi) = -P(\xi)$, the probability of a shot falling between 0 and $-\dfrac{x}{\epsilon_x}$ being numerically equal to the probability of its falling between 0 and $+\dfrac{x}{\epsilon_x}$.

The probability $p_{x_{12}}$ that the range error of a point of impact will lie between x_1 and x_2 may be determined from the tabulated values of $P(\xi)$, since

$$p_{x_{12}} = \frac{k}{\sqrt{\pi}} \int_{\xi_1}^{\xi_2} e^{-k^2\xi^2} d\xi = \frac{k}{\sqrt{\pi}} \int_{\xi_1}^{0} e^{-k^2\xi^2} d\xi + \frac{k}{\sqrt{\pi}} \int_{0}^{\xi_2} e^{-k^2\xi^2} d\xi$$

$$= -\frac{k}{\sqrt{\pi}} \int_{0}^{\xi_1} e^{-k^2\xi^2} d\xi + \frac{k}{\sqrt{\pi}} \int_{0}^{\xi_2} e^{-k^2\xi^2} d\xi = P(\xi_2) - P(\xi_1) \qquad (2)$$

Therefore the probability $p_{x_{12}}$ for the limits x_1 and x_2 may be obtained by subtracting $P(\xi_1)$ from $P(\xi_2)$, these values being taken from the table for $\xi_1 = \dfrac{x_1}{\epsilon_x}$ and $\xi_2 = \dfrac{x_2}{\epsilon_x}$. If x_1 and x_2 bracket the C.I., x_1 and hence ξ_1 and $P(\xi_1)$ are negative. The value of $p_{x_{12}}$ also expresses the proportion of shots that may be expected to fall between x_1 and x_2.

Instead of using a table to evaluate $p_{x_{12}}$, a curve may be used. In Fig. 256 is plotted $\dfrac{k}{\sqrt{\pi}} \displaystyle\int_{-\infty}^{\xi} e^{-k^2\xi^2} d\xi$ vs. ξ, or $[P(\xi) - P(-\infty)]$ vs. ξ.

The abscissae represent range errors expressed with the range probable error as a unit, and the ordinates the probability that the range error will lie between $-\infty$ and ξ probable errors. The ordinates also express the probability of a short with respect to a target located at any point ξ.

Since, by Eq. (2)

$$p_{x_{12}} = P(\xi_2) - P(\xi_1)$$

it is apparent that the probability of a range error between x_1 and x_2, and the probable proportion of shots between these limits, is expressed

directly by the difference between the corresponding ordinates of the curve.

Similarly it may be shown that the probability $p_{z_{12}}$ that the deflection error of a shot will lie between z_1 and z_2 is

$$p_{z_{12}} = \frac{k}{\sqrt{\pi}} \int_{\zeta_1}^{\zeta_2} e^{-k^2\zeta^2} d\zeta = P(\zeta_2) - P(\zeta_1)$$

where $\zeta = \frac{z}{\epsilon_z}$ and ϵ_z is the deflection probable error. The probability $p_{z_{12}}$ may be obtained from Table I or from the curve (Fig. 256) in the same manner as was $p_{x_{12}}$.

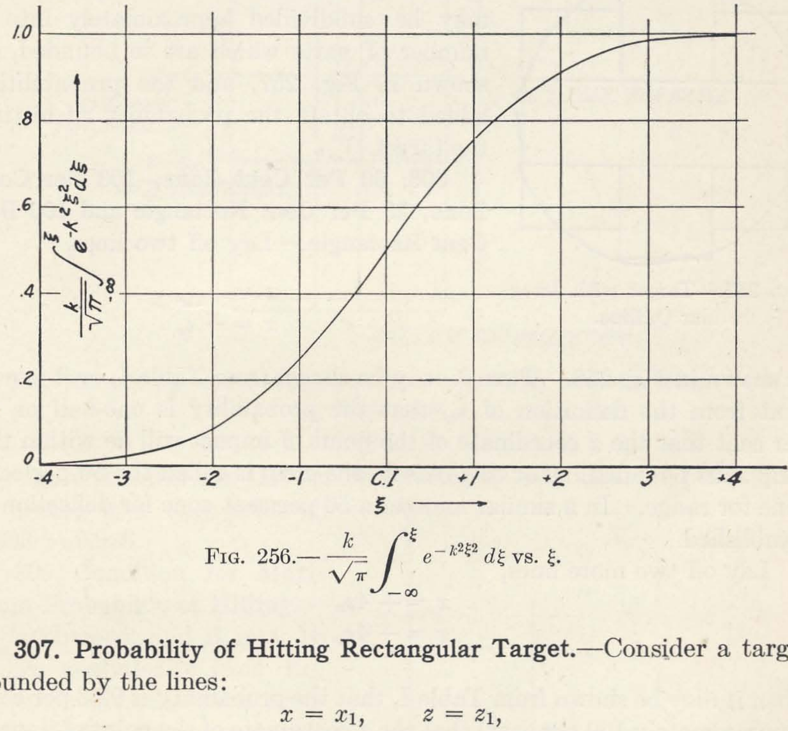

FIG. 256.—$\frac{k}{\sqrt{\pi}} \int_{-\infty}^{\xi} e^{-k^2\xi^2}\, d\xi$ vs. ξ.

307. Probability of Hitting Rectangular Target.—Consider a target bounded by the lines:

$$x = x_1, \qquad z = z_1,$$
$$x = x_2, \qquad z = z_2.$$

It is desired to ascertain the probability of hitting such a target.

To compute this probability, the assumption is made that the probability that the range error lies between x_1 and x_2 is independent of the probability that the deflection error lies between z_1 and z_2. Thus the probability that x lies between x_1 and x_2 *and* that z lies between z_1 and z_2 is the *product* of the probability that x lies between x_1 and x_2 and the

probability that z lies between z_1 and z_2. If the probability of hitting the rectangle is designated by $p_\square$,

$$p_\square = p_{x_{12}} \cdot p_{z_{12}} = \left(\frac{k}{\sqrt{\pi}}\int_{\xi_1}^{\xi_2} e^{-k^2\xi^2}d\xi\right)\cdot\left(\frac{k}{\sqrt{\pi}}\int_{\zeta_1}^{\zeta_2} e^{-k^2\zeta^2}d\zeta\right) \qquad (3)$$

$$= [P(\xi_2) - P(\xi_1)]\cdot[P(\zeta_2) - P(\zeta_1)]$$

The integrals in the product may be evaluated by means of Table I, Section 306, or by the curve in Fig. 256.

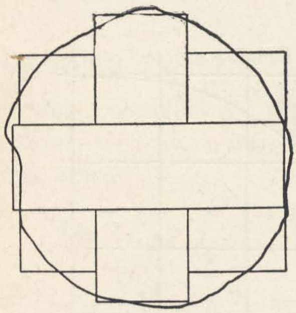

FIG. 257.—Target with Irregular Outline.

In the event that the target is not bounded by lines parallel to the coordinate axes, it may be subdivided approximately into a number of parts which are so bounded, as shown in Fig. 257, and the probabilities added to obtain the probability of hitting the target.

308. 50 Per Cent Zone, 100 Per Cent Zone, 25 Per Cent Rectangle and 100 Per Cent Rectangle.—Lay off two lines,

$$x = + \epsilon_x$$
$$x = - \epsilon_x$$

as shown in Fig. 258. Then it may be shown from Table I, or it is evident from the definition of ϵ_x, that the probability is one-half or 50 per cent that the x coordinate of the point of impact will lie within the strip thus bounded. For this reason, the strip is called the 50 per cent zone for range. In a similar manner a 50 per cent zone for deflection is established.

Lay off two more lines,

$$x = + 4\epsilon_x$$
$$x = - 4\epsilon_x.$$

Then it may be shown from Table I, that the probability is 99.3 per cent (approximately 100 per cent) that the x coordinate of the point of impact will lie between these lines. For this reason the strip bounded by these lines is called the 100 per cent zone for range. In a similar manner a 100 per cent zone for deflection may be established.

The rectangle formed by the intersection of the two 50 per cent zones, bounded by the heavy line in Fig. 258, is called the 25 per cent rectangle since the probability of hitting it is $0.50 \times 0.50 = 0.25$, and 25 per cent of the shots may be expected to fall within it. The largest rectangle in

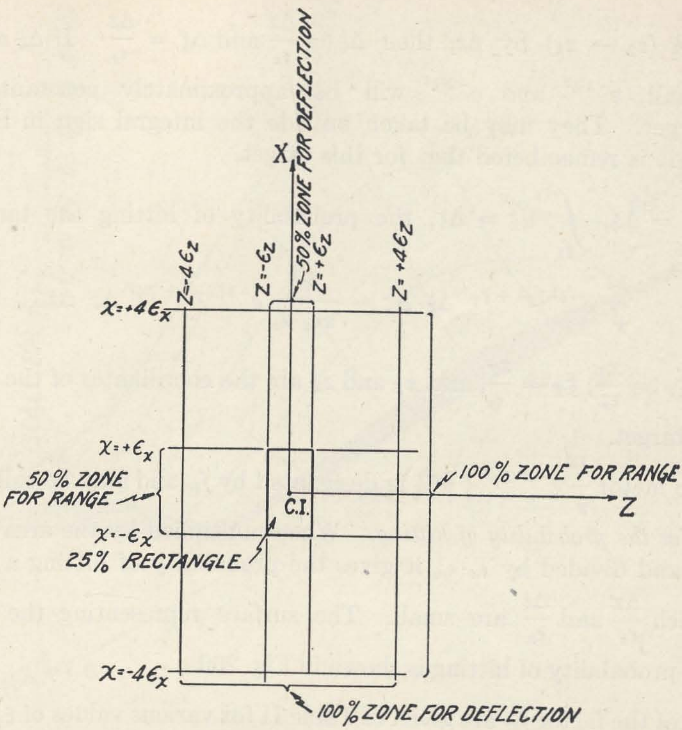

FIG. 258.—50 per cent and 100 per cent Zones, 25 per cent and 100 per cent Rectangles.

the figure is called the 100 per cent rectangle although the probability of hitting it is only $0.993 \times 0.993 = 0.986$.

309. Condition for Maximum Probability of Hitting.—It is obvious, and it may be shown analytically from Eq. (3), that the maximum probability of hitting a rectangle of given dimensions bounded by lines parallel to the X and Z axes, as shown in Fig. 259, is obtained when the center of impact C.I. is placed on the center of the rectangle. If $(x_2 - x_1)$ is designated by

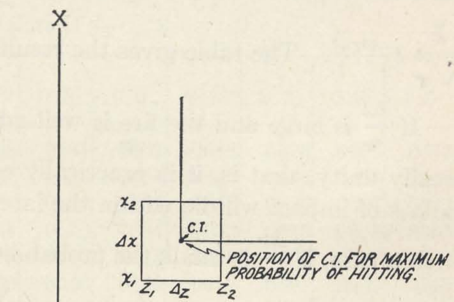

FIG. 259.—Positions of the C.I. with Respect to the Target.

Δx and $(z_2 - z_1)$ by Δz, then $\Delta\xi = \frac{\Delta x}{\epsilon_x}$ and $\Delta\zeta = \frac{\Delta z}{\epsilon_z}$. If $\Delta\xi$ and $\Delta\zeta$ are small, $e^{-k^2\xi^2}$ and $e^{-k^2\zeta^2}$ will be approximately constant over the target. They may be taken outside the integral sign in Eq. (3) and, if it is remembered that for this target,

$\int_{\xi_1}^{\xi_2} d\xi = \Delta\xi$, $\int_{\zeta_1}^{\zeta_2} d\zeta = \Delta\zeta$, the probability of hitting the target is

$$\frac{k^2}{\pi} e^{-k^2(\xi_T^2 + \zeta_T^2)} \Delta\xi \cdot \Delta\zeta = \frac{k^2}{\pi\epsilon_x \cdot \epsilon_z} e^{-k^2(\xi_T^2 + \zeta_T^2)} \Delta x \cdot \Delta z \tag{4}$$

where $\xi_T = \frac{x_T}{\epsilon_x}$, $\zeta_T = \frac{z_T}{\epsilon_z}$, and x_T and z_T are the coordinates of the center of the target.

The factor $\frac{k^2}{\pi} e^{-k^2(\xi_T^2 + \zeta_T^2)}$ is designated by $f_{\xi\zeta}$ and may be called the *factor for the probability of hitting.* When multiplied by the area of the target and divided by $\epsilon_x \cdot \epsilon_z$, it gives the probability of hitting a target for which $\frac{\Delta x}{\epsilon_x}$ and $\frac{\Delta z}{\epsilon_z}$ are small. The surface representing the factor for the probability of hitting is shown in Fig. 260.

Values of the factor $f_{\xi\zeta}$ are given in Table II for various values of $\xi_T = \frac{x_T}{\epsilon_x}$ and $\zeta_T = \frac{z_T}{\epsilon_z}$. As indicated by Eq. (4), for a given pair of values of ξ_T and ζ_T, the factor $f_{\xi\zeta}$ is obtained by multiplying $\frac{k}{\sqrt{\pi}} e^{-k^2\xi_T^2}$ by $\frac{k}{\sqrt{\pi}} e^{-k^2\zeta_T^2}$. The table gives the results of the multiplication.

If $\frac{\Delta z}{\epsilon_z}$ is large and the fire is well adjusted in direction, $p_{z_{12}}$ is practically unity, that is, it is practically certain that the deflection of the points of impact will lie within the lateral limits z_1z_2 of the target. In such a case, if $\frac{\Delta x}{\epsilon_x}$ is small, the probability of hitting a rectangle of depth Δx is given by

$$\left(\frac{k}{\sqrt{\pi}} e^{-k^2\xi_T^2}\right) \cdot \frac{\Delta x}{\epsilon_x}.$$

The function $\frac{k}{\sqrt{\pi}} e^{-k^2\xi^2}$ may be called the factor for the probability of hitting a broad target. If it is multiplied by Δx and divided by ϵ_x,

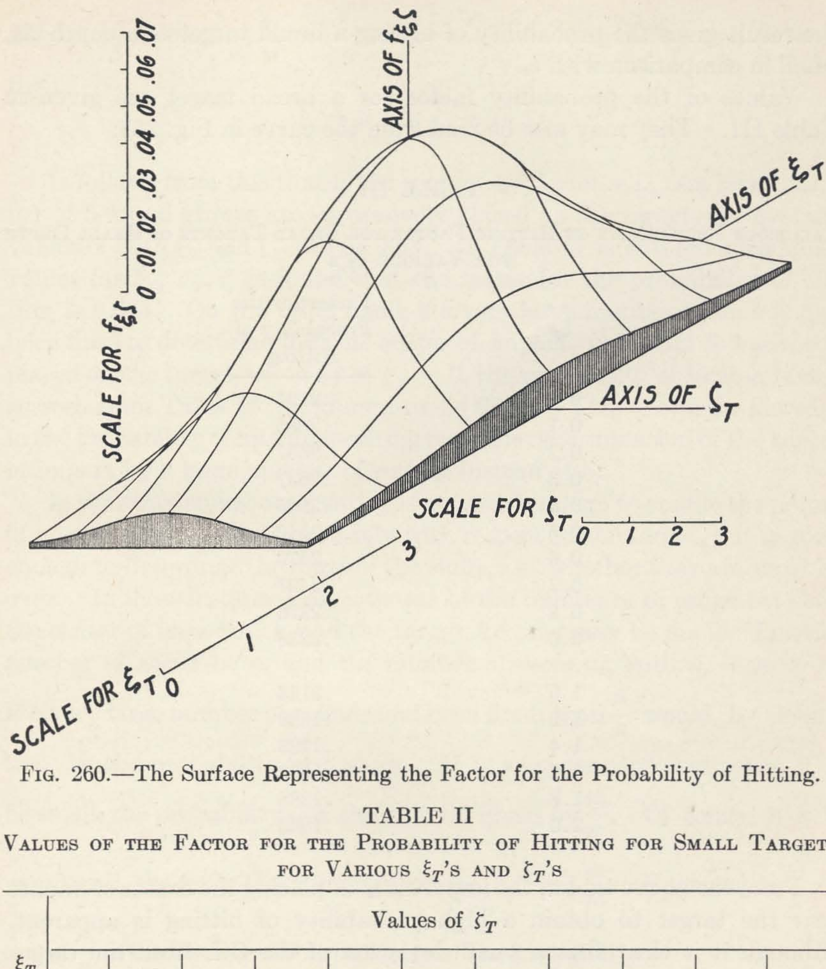

FIG. 260.—The Surface Representing the Factor for the Probability of Hitting.

TABLE II

VALUES OF THE FACTOR FOR THE PROBABILITY OF HITTING FOR SMALL TARGETS FOR VARIOUS ξ_T'S AND ζ_T'S

ξ_T	Values of ζ_T										
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	.0724	.0722	.0718	.0710	.0698	.0684	.0667	.0648	.0626	.0602	.0577
0.1	.0722	.0721	.0716	.0708	.0697	.0682	.0666	.0646	.0624	.0601	.0575
0.2	.0718	.0716	.0711	.0703	.0692	.0678	.0661	.0642	.0620	.0597	.0572
0.3	.0710	.0708	.0703	.0695	.0684	.0670	.0654	.0635	.0613	.0590	.0565
0.4	.0698	.0697	.0692	.0684	.0673	.0660	.0643	.0625	.0604	.0581	.0556
0.5	.0684	.0683	.0678	.0670	.0660	.0646	.0630	.0612	.0591	.0569	.0545
0.6	.0667	.0666	.0661	.0654	.0643	.0630	.0614	.0597	.0577	.0555	.0531
0.7	.0648	.0646	.0642	.0635	.0625	.0612	.0597	.0579	.0560	.0539	.0516
0.8	.0626	.0625	.0620	.0613	.0604	.0591	.0577	.0560	.0541	.0521	.0499
0.9	.0602	.0601	.0597	.0590	.0581	.0569	.0555	.0539	.0521	.0501	.0480
1.0	.0577	.0575	.0572	.0565	.0556	.0545	.0531	.0516	.0498	.0480	.0459

the result gives the probability of hitting a broad target of a depth Δx, small in comparison with ϵ_x.

Values of the probability factor for a broad target are given in Table III. They may also be read from the curve in Fig. 253.

TABLE III

VALUES OF PROBABILITY OF HITTING FACTOR FOR BROAD TARGETS OF SMALL DEPTH FOR VARIOUS ξ_T'S

ξ_T	Factor for the Probability of Hitting
0.0	.2691
0.1	.2685
0.2	.2667
0.3	.2637
0.4	.2595
0.5	.2542
0.6	.2479
0.7	.2407
0.8	.2326
0.9	.2238
1.0	.2143
1.2	.1939
1.4	.1723
1.6	.1503
1.8	.1288
2.0	.1083

From the above tables, the importance of placing the center of impact near the target to obtain a high probability of hitting is apparent, although it is clear that a small deviation of the C.I. from the target will reduce the probability of hitting only slightly.

310. Determination of the C.I.—In general, the center of impact c.i. determined by n rounds will differ in position from the C.I. In other words, if the coordinates of the c.i. are x_i, z_i, in general, $x_i \neq 0$, $z_i \neq 0$. It can be shown that if $\bar{x}_i$, $\bar{z}_i$ represent the mean or average absolute values of x_i and z_i for a large number of groups of n rounds each

$$\bar{x}_i = \frac{\epsilon_x}{0.845\sqrt{n}}$$

$$\bar{z}_i = \frac{\epsilon_z}{0.845\sqrt{n}}.$$

If $\bar{\xi}_i$ and $\bar{\zeta}_i$ represent $\frac{\bar{x}_i}{\epsilon_x}$ and $\frac{\bar{z}_i}{\epsilon_z}$ respectively, for 5-round groups ($n = 5$) then,

$$\bar{\xi}_i = 0.53, \quad \bar{\zeta}_i = 0.53.$$

It follows from this that if the centers of impact, c.i., of a large number of 5-round groups are successively placed on the target, the average values of both ξ_T and ζ_T will be 0.53. If Table II is entered with these values for ξ_T, ζ_T, it is found that the factor for the probability of hitting is 0.064. On the other hand, if a very large number of rounds had been fired to determine the true center of impact, C.I., and it had been placed on the target, i.e., if $\xi_T = \zeta_T = 0$, the probability of hitting factor as seen from Table II would increase to 0.072. This shows the increase in the probability of hitting resulting from the determination of the center of impact by a large number of rounds instead of 5.

In some instances, observation is not good enough to enable the points of impact to be plotted accurately with respect to the target, but is good enough to determine the sense of the shots, i.e., whether they are short or over. In these instances, an estimate of the difference in range between the center of impact C.I. and the target, i.e., x_T, may be made. Let the number of *shorts* be n_s and the number of *overs* n_o, with $n_o + n_s = n$. If a very large number of rounds had been fired, than $\frac{n_s}{n}$ would, by definition, be the probability of a short. It is now *assumed* that, even if n be small, the probability of a short is still given by $\frac{n_s}{n}$. Of course if n is very small, the probability may differ greatly from $\frac{n_s}{n}$. However, in all cases, $\frac{n_s}{n}$ is the best available estimate of the probability.

In Section 306, it was shown that the probability of a short, p_s, is

$$\frac{k}{\sqrt{\pi}} \int_{-\infty}^{\xi_T} e^{-k^2 \xi_T^2} d\xi_T$$

where $\xi_T = \frac{x_T}{\epsilon_x}$.

Figure 256 is now reproduced in Fig. 261.

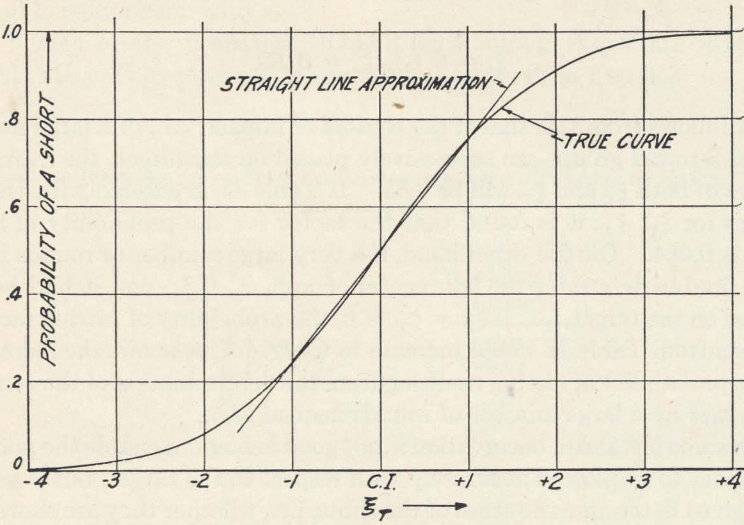

FIG. 261.—Probability of a Short vs. ξ_T.

A secant to the curve is drawn through the points $(-1, .25)$, $(0, .5)$, $(+1, .75)$ and it is observed that for values of $\frac{n_s}{n}$ that lie between .1 and .9 the secant approximates the curve closely. Since the slope of the secant is $\frac{1}{4}$ and it passes through the point $(0, \frac{1}{2})$, it may be assumed that for such values of $\frac{n_s}{n}\left(\text{i.e., } .1 < \frac{n_s}{n} < .9\right)$,

$$\frac{n_s}{n} = \frac{1}{2} + \frac{\xi_T}{4}.$$

From this it is evident that

$$\frac{\xi_T}{4} = \frac{n_s}{n} - \frac{1}{2} = \frac{2n_s - n}{2n} = \frac{n_s + n_s - n_s - n_o}{2n} = \frac{n_s - n_o}{2n}$$

and

$$\xi_T = \frac{2(n_s - n_o)}{n}; \quad \text{or} \quad x_T = \frac{2(n_s - n_o)\epsilon_x}{n} \tag{5}$$

This may be expressed as the rule *that the distance of the target from the center of impact* should be approximately equal to the probable error multiplied by $\frac{2(n_s - n_o)}{n}$ in cases where $.1 < \frac{n_s}{n} < .9$.

The smaller the number of rounds, the less precise will be the estimate of x_T obtained in this way.

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CHAPTER XII

BOMBING FROM AIRPLANES

LIST OF SYMBOLS USED IN THIS CHAPTER AND THEIR MEANING

Symbol	Meaning
O	The origin of the coordinate system, the airplane.
O_g	The vertical projection of O on the ground.
OA	The course or the direction of u_h.
OG	The direction of the track or the direction of v_g.
OP	The deflection axis of the telescopic sight, perpendicular to OT_x and in the XY plane.
OT	The line from the airplane to the target.
OT_x	The line from the airplane to the projection of T on the X_g axis.
$\left.\begin{matrix}X\\Y\\Z\end{matrix}\right\}$	The coordinate axes.
$\left.\begin{matrix}X_g\\Z_g\end{matrix}\right\}$	The vertical projections of X and Z on the ground.
T_x	The projection of T on the X_g axis.
$\left.\begin{matrix}T\\T_0\\T_\omega\end{matrix}\right\}$	The positions of the target at time, t, the instant of release, and the instant of impact, respectively.
h	Constant occurring in the expression for the standard density structure, $\rho(y) = \rho_0 e^{-h(y_\omega - y)}$.
p	Distance of the airplane above the target.
q	The movement of the target during the time of flight of the bomb, t_ω.
$\left.\begin{matrix}q_x\\q_y\\q_z\end{matrix}\right\}$	The components of q along the X, Y, and Z axes.
r	The linear trail of the bomb.
s	Distance above the target.
t	Time.

Symbol	Meaning
t_ω	Time of flight of the bomb; at instant of impact, $t = t_\omega$.
u	Air speed of the airplane.
u_h, u_y	Horizontal and vertical components of u.
v_g	Ground speed of the airplane = horizontal component of the speed of the airplane with respect to the ground.
w	Velocity of the air with respect to the coordinate system moving with the airplane.
$w_h(0)$	Horizontal component of w at the airplane, where $y = 0$.
$w_h(y)$	The horizontal component of w as a function of y.
w_x, w_y, w_z	The components of w along the three axes.
$w_x(0)$, $w_y(0)$, $w_z(0)$	The components of w at the airplane.
$w_x(y)$, $w_z(y)$	The x and z components of w as functions of y.
w_N, w_E	Components of the wind measured with respect to the ground, towards the north and east, respectively.
$w_N(p)$, $w_E(p)$	Values of w_N and w_E at the airplane.
$w_N(s)$, $w_E(s)$	w_N and w_E as functions of the distance, s, above the target.
$\overline{w}_h$	The horizontal ballistic wind referred to coordinates moving with the airplane.
$\overline{w}_p$	The horizontal ballistic wind with reference to coordinates moving with the air at the airplane.
$\overline{w}_{pN}$, $\overline{w}_{pE}$	The north and east components of $\overline{w}_p$.
$\overline{w}_{px}$, $\overline{w}_{pz}$	The x and z components of $\overline{w}_p$.
$\overline{w}_x$, $\overline{w}_z$	The x and z components of $\overline{w}_h$.
x, y, z	The coordinates of a point in the coordinate system moving with the airplane.
x_T, y_T, z_T	The coordinates of the target at any time, t.

Symbol	Meaning
$\left.\begin{matrix} x_{T_0} \\ y_{T_0} \\ z_{T_0} \end{matrix}\right\}$	The coordinates of the target at the instant of release, $t = 0$.
$\left.\begin{matrix} x_{T_\omega} \\ y_{T_\omega} \\ z_{T_\omega} \end{matrix}\right\}$	The coordinates of the target at the instant of impact, t_ω.
$\left.\begin{matrix} x_\omega \\ y_\omega \\ z_\omega \end{matrix}\right\}$	The coordinates of the point of impact, Ω.
α	Azimuth of $\overline{w}_p$ measured from the north.
β	Position angle of the target for range (measured from the vertical) at any time, t.
β_0	Value of β at the instant the bomb is released, $t = 0$.
β'	Travel angle of target for range (measured from the vertical).
γ	Position angle of the target for deflection (measured from the XY plane) at any time, t.
γ_0	Value of γ at the instant the bomb is released, $t = 0$.
γ'	Travel angle of target for deflection (measured from the XY plane).
θ_0	Diving angle.
λ	Azimuth of X measured from the north.
ρ	Density of the air.
$\rho(y)$	Density of the air as a function of y.
$\rho(y_\omega)$	Density of the air at the point of fall.
ρ_0	Standard air density at the target = 1.2034 grams per liter.
τ	Trail angle.
ϕ	Azimuth of the trail.
ψ	Drift angle.
Ω	Point of impact.

BOMBING FROM AIRPLANES

In bombing from an airplane, the bomb is simply released from the airplane and allowed to fall. As it falls to the ground, it is acted upon by the forces of gravity and air resistance. The magnitude and direction of the latter will depend upon the velocity and direction of motion of the bomb with respect to the air.

The problem here considered is how to determine the direction of flight of the airplane from a point from which the target is observed by the bomber, and how to time the release so that, after falling to the

ground under the influence of the forces mentioned, the bomb will strike the target.

311. The Movement of the Airplane.—Assume an airplane flying in a straight line with an *air speed* (speed with reference to the air) equal to u. The air speed will have a vertical component u_y and a horizontal component u_h such that

$$u^2 = u_y^2 + u_h^2.$$

The horizontal component of the speed of the airplane with respect to the ground is designated by v_g and called *the ground speed.* In this treatment it will be assumed that v_g remains constant in magnitude and direction during the time of flight of the bomb, designated by t_ω.

If no wind is blowing, the ground speed v_g will be the same as the horizontal component of the air speed of the plane, u_h. If, however, a wind is blowing this ceases to be the case. Let the horizontal component of the velocity of the wind be represented in magnitude and direction by the line OW, and the horizontal component of the air speed of the airplane, u_h, by the line OA in Fig. 262. It is evident then that the ground speed v_g will be represented in direction and magnitude by the line OG, the diagonal of a parallelogram of which OA and OW are the sides.

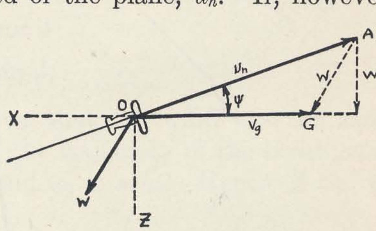


FIG. 262.—The Course, the Track, and the Drift Angle, ψ.

The line OA is horizontal and lies in the vertical plane through the fore and aft axis of the airplane. It points in the direction of the course indicated by the magnetic compass in the ship and its direction is called the *course.* The line OG is called the *track.* The angle GOA, formed by the course and the track, is called the *drift angle,* and is designated by ψ.

312. The Coordinate System.—In the chapter on exterior ballistics, a coordinate system attached to the earth was employed. In the discussion of bombing, it is more convenient to use a coordinate system, the origin of which is attached to the airplane and moves with it, since the bomber must make all his measurements directly with reference to the airplane and only indirectly with reference to the earth.

A rectangular coordinate system is employed with its origin O always at the airplane, its X axis pointing in a direction the exact opposite of the track, OG, its Y axis pointing vertically downward, and its Z axis perpendicular to these with its positive direction to the leeward,

as shown in Fig. 263. X_g and Z_g are the vertical projections of the X and Z axes on the ground, and O_g is the vertical projection of O.

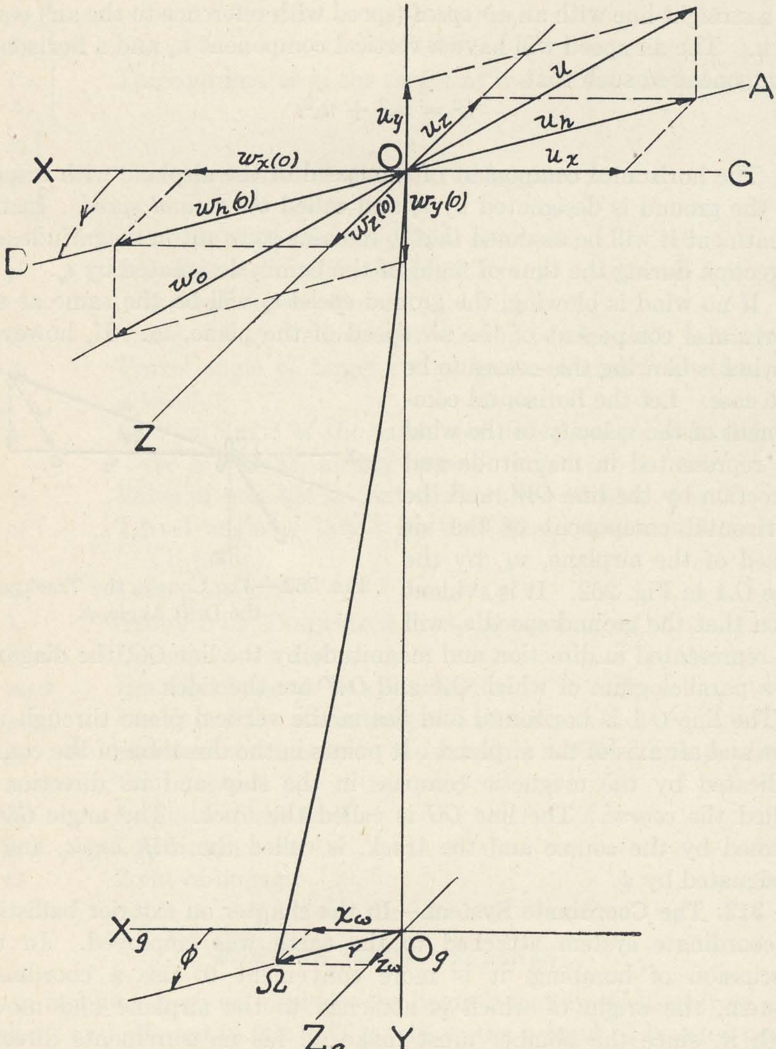


FIG. 263.—Coordinate System.

313. Initial Conditions, Air Structure, Point of Fall.—The time when the bomb is released is given by $t = 0$. At $t = 0$, the bomb is at the airplane O and motionless with respect to the coordinate system. Thus

the initial values of the coordinates and the velocities of the bomb are zero. The velocity of the air with respect to the airplane, numerically equal to u and opposite in direction, is defined as the wind at the airplane, w_o. In general, the wind at any point in the reference frame is the velocity of the air with respect to the reference frame at that point.

The components of the wind w are designated by w_x, w_y, and w_z. As in Section 285 of Chapter X, they are considered to be functions of y, that is,

$$w_x = w_x(y), \qquad w_y = w_y(y), \qquad w_z = w_z(y).$$

The horizontal component of the wind at the airplane, $w_h(0)$, is numerically equal to u_h and, as shown in Fig. 263, makes an angle ψ with the X axis. Thus the x and z components of the wind velocity at the plane, $w_x(0)$ and $w_z(0)$, are given by

$$w_x(0) = u_h \cos \psi$$

$$w_z(0) = u_h \sin \psi.$$

The standard air structure assumes that the wind has the same strength and direction at all points of the trajectory of the bomb as at the airplane, and that the vertical wind w_y is zero. Hence, if the air structure is standard,

$$w_x(y) = w_x(0) = u_h \cos \psi$$

$$w_z(y) = w_z(0) = u_h \sin \psi$$

$$w_y(y) = 0.$$

From this it follows that, for standard wind structure, $w_h(y)$, the horizontal component of w is given at all points by

$$w_h(y) = u_h$$

and its direction is always OB, which makes an angle ψ with the X axis.

The standard density structure for bombing is given by

$$\rho(y) = \rho_0 e^{-h(y_\omega - y)}$$

where ρ_0 is the standard air density of 0.07513 lb. per ft.^{3}, or 1.2034 grams per liter, and y_ω is the y coordinate of the point of fall. The standard temperature is taken to be 518° absolute on the Fahrenheit scale. (See Section 285, Chapter X.)

Under the influence of gravity, the bomb falls in the general direction of the Y axis. The horizontal component of the wind w_h, however, will blow the bomb away from the Y axis in the vertical plane including OB, which makes an angle ψ with the XY plane.

If the wind structure is standard, the direction of w_h will always be

OB, the horizontal component of the motion of the bomb will lie in the vertical plane including OB, and the point of fall of the bomb, designated by Ω, will therefore be in the vertical plane including OB. On the other hand, if the wind structure is not standard, Ω will not lie in this plane.

The horizontal distance of Ω from the Y axis, $O_g\Omega$, is called the *trail* and is designated by r. The angle $X_gO_g\Omega$ is designated by ϕ and is called the *azimuth of the trail.* As explained above, if the wind structure is standard, $\phi = \psi$. Since $O_g\Omega$ makes an angle ϕ with the X axis, the x component of $O_g\Omega$ is $r \cos \phi$. This is called *the range component of the trail* and is designated by x_ω. The z component of $O_g\Omega$ is $r \sin \phi$. This is called the *deflection component of the trail* and is designated by z_ω. The y coordinate of the point of fall is called the depth of the point of fall and is designated by y_ω.

The trajectory, as viewed by an observer motionless with respect to the airplane, is shown in Fig. 263. As further illustrations, Figs. 264 and

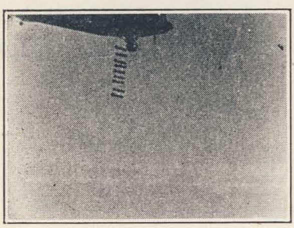


FIG. 264.—Falling Bombs as Viewed from the Side of an Airplane.

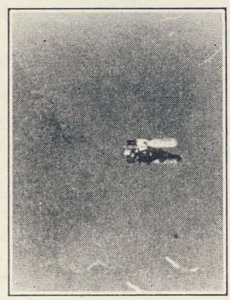


FIG. 265.—Falling Bombs Viewed from the Airplane Itself.

265 are given. They are photographs of falling bombs taken by an observer motionless with respect to the coordinate system of the bombing airplane. To an observer on the ground, the trajectory will have a quite different appearance as may be seen in Fig. 210 of Chapter X.

314. Coordinates and Position Angles of the Target.—The position of the target at any time t in the chosen reference frame moving with the airplane is designated by T (Fig. 266). Its position when $t = 0$ is designated by T_0, and at t_ω, the time of impact, by T_ω. The x, y, and z coordinates of T, T_0, and T_ω are designated by x_T, y_T, z_T; x_{T_0}, y_{T_0}, z_{T_0}; and x_{T_ω}, y_{T_ω}, z_{T_ω}, respectively. The y coordinate of the target will be called the *depth* of the target. The coordinate y_{T_0} is sometimes called the *altitude at release* and y_{T_ω} the *altitude at impact,* since they are equal to the altitude of the airplane above the target at the times of release and impact, respectively. If the target is on the ground, of course, $y_{T_\omega} = y_\omega$.

As a rule, there will be a considerable motion of the target with respect to the plane. The x, y, and z components of the travel of the target during the time of flight t_ω are designated by

$$q_x,\ q_y,\ \text{and } q_z.$$

An observer on the airplane cannot measure the distances x_T and z_T directly. However, they may be measured if the value of y_T is known, and if the direction of the target from the airplane, OT, is known.

To determine the direction of the line OT, two angles, β and γ (Fig. 266), are defined as follows:

$$\tan\beta = \frac{-x_T}{y_T}$$
$$\tan\gamma = \frac{z_T}{(y_T^2 + x_T^2)^{\frac{1}{2}}}. \tag{1}$$

It is evident that γ is the angle between two lines OT_x and OT, both of which lie in a plane including the Z axis and T_x. It is therefore a rotation about a line perpendicular to OT_x and the Z axis. This perpendicular is designated by OP (Fig. 266) and lies in the XY plane.

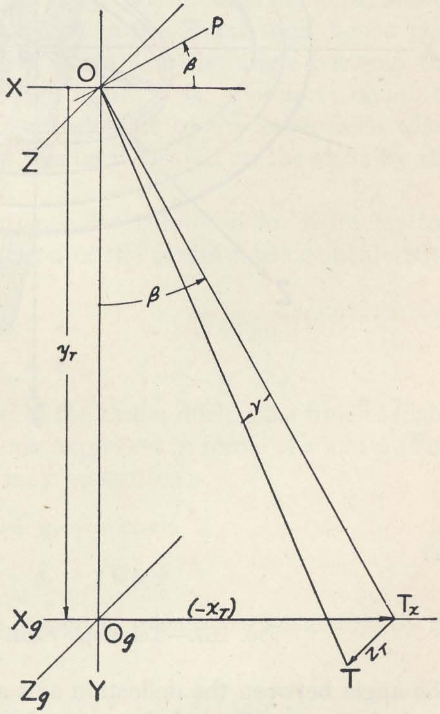


FIG. 266.—Coordinates and Position Angles of the Target.

The angle β is called the *range angle* of the target and γ is called the *deflection angle* of the target. The two angles β and γ are also called the *position angles* of the target since, together with y_T, they determine the position of the target with respect to the airplane.

315. The Measurement of the Position Angles and the Drift Angle.—If the position of the target is to be determined by the angles β and γ, an instrument is required to measure them. For this purpose a telescopic sight is provided which points through an opening in the floor of the fuselage, as shown in Fig. 267.

Since γ is a rotation of a line about OP, to measure it the telescope is pointed at T_x and then turned about OP, called the *deflection axis*, until it points to T. The angle through which it is turned is equal in magnitude to γ. OP is perpendicular to OT_x in the XY plane. Therefore,

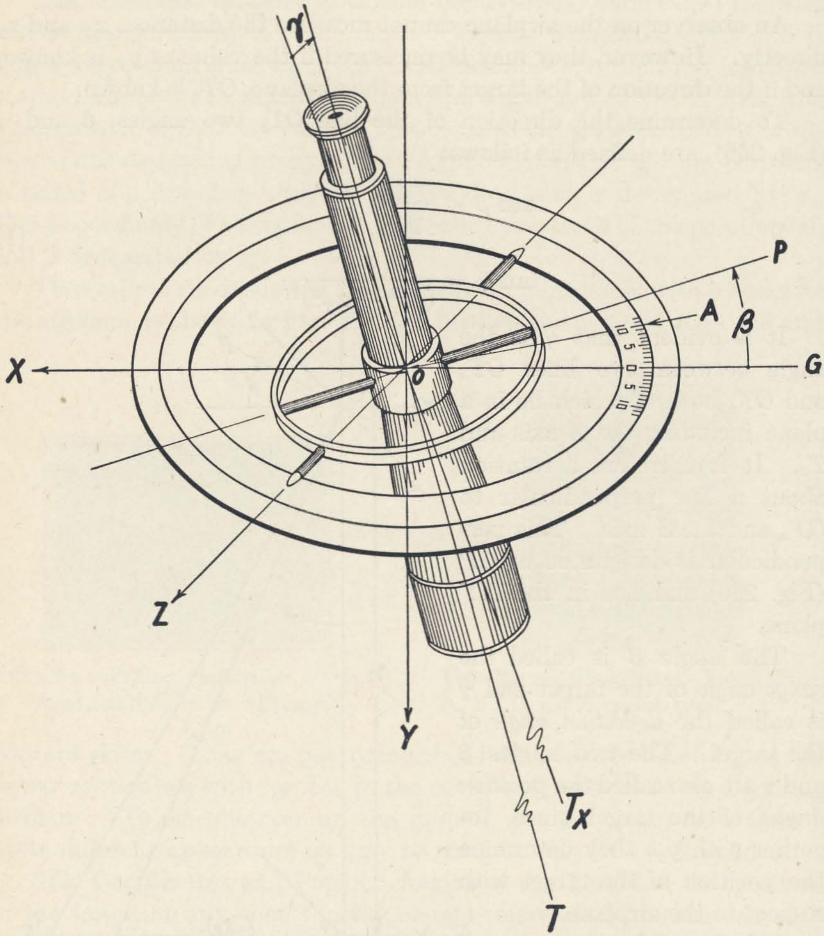


FIG. 267.—Telescopic Sight for Measuring β and γ.

the angle between the deflection axis and the horizontal is equal to the angle between OT_x and the vertical OO_g, which is β.

The deflection axis OP must be perpendicular to OT_x and to the Z axis. To provide for this setting, OP can be turned about a horizontal axis which is kept aligned with the Z axis. This horizontal axis, about which OP turns, is called the *range axis*. The ends of the range axis are

attached to a ring which is kept horizontal and can be turned about the vertical.

The telescope has two cross hairs making a right angle with each other. One is parallel to the deflection axis and is called the deflection cross hair. The other, which is parallel to the range axis when $\gamma = 0$, is called the range cross hair. With the telescope in the XY plane ($\gamma = 0$), the intersection of the two cross hairs is sighted on an object stationary with respect to the ground, and the range cross hair is kept on the object by the rotation of the deflection axis about the range axis. It will then usually happen that the object moves away from the deflection cross hair. In this event, the ring, to which the range axis is attached, is turned about the vertical in such a manner that a stationary object which is seen to coincide with the intersection of the two cross hairs remains in coincidence as the object is followed by the rotation of the deflection axis about the range axis.* This is the procedure by which the range axis is kept parallel to the Z axis and hence perpendicular to the track. The drift angle ψ is the angle between the *track OG* and the *course OA* (Fig. 262). ψ is, therefore, equal to the angle between OA and the perpendicular to the range axis when this axis is properly adjusted, and can be measured on the sight by the graduations shown at A, Fig. 267.

316. The Conditions for Hitting.—The condition for a hit is that at t_ω, the time of impact, the position of the target must coincide with the point of fall Ω, or, that

$$x_{T_\omega} = x_\omega$$

$$z_{T_\omega} = z_\omega \dagger.$$

If the components of the travel of the target during the time of flight are q_x, q_y, and q_z, and if x_ω and z_ω are expressed in terms of r and ϕ (Fig. 263), the conditions given above may be written:

$$\begin{aligned} x_{T_\omega} &= x_{T_0} + q_x = r\cos\phi \\ z_{T_\omega} &= z_{T_0} + q_z = r\sin\phi \end{aligned} \tag{2}$$

If the values of β and γ at the instant of release are designated by β_0 and γ_0, Eqs. (1) indicate that

$$x_{T_0} = -\,y_{T_0}\tan\beta_0;\; z_{T_0} = (y_{T_0}{}^2 + x_{T_0}{}^2)^{\frac{1}{2}}\tan\gamma_0.$$

* Since OG is the direction of the ground speed, objects on the ground have no component of motion perpendicular to it. If objects on the ground have no component of motion perpendicular to the deflection cross hair, the cross hair must lie in the vertical plane through OG and must therefore be perpendicular to Z.

† It is assumed that since T and Ω are both on the ground, $y_\omega = y_{T_\omega}$.

By inserting these in Eqs. (2), the conditions for hitting are obtained in the form

$$y_{T_0}\cdot\tan\beta_0 = q_x - r\cos\phi$$

$$(y_{T_0}{}^2 + x_{T_0}{}^2)^{\frac{1}{2}}\cdot\tan\gamma_0 = -q_z + r\sin\phi$$

or

$$\tan\beta_0 = \frac{q_x - r\cos\phi}{y_{T_0}}$$

$$\tan\gamma_0 = \frac{-q_z + r\sin\phi}{(y_{T_0}{}^2 + x_{T_0}{}^2)^{\frac{1}{2}}}.$$

If it is assumed that the equations for hitting are satisfied, then x_{T_0} in the denominator of the right-hand side of the last equation may be obtained from Eqs. (2), i.e., $x_{T_0} = r\cos\phi - q_x$. With this substitution, the conditions for hitting are obtained in the form

$$\tan\beta_0 = \frac{q_x - r\cos\phi}{y_{T_0}}$$
$$\tan\gamma_0 = \frac{-q_z + r\sin\phi}{[y_{T_0}{}^2 + (r\cos\phi - q_x)^2]^{\frac{1}{2}}} \tag{3}$$

These are the conditions which the position angles, β and γ, must satisfy at the instant of release if a hit is to be obtained.

Since distances on the ground can be determined at the airplane only by means of the angles which they subtend at the airplane and the depth of the target y_T, it is desirable to express the right-hand sides of Eqs. (3) in terms of angles which can be measured at the plane.

Now r can be expressed in terms of an angle τ, called the trail angle, if this is defined by the relation

$$\tan\tau = \frac{r}{y_{T_0}} \tag{4}$$

The angle τ is thus the angle subtended at the airplane, at the instant of release when $y_T = y_{T_0}$, by the line $O_g\Omega$ (Fig. 268), which, by definition, has a length r and makes an angle ϕ with the X_g axis.

Similarily, q_x and q_z may be expressed in terms of β' and γ', called the *travel angles* of the target, which are defined as follows:

$$\tan\beta' = \frac{q_x}{y_{T_0}} \tag{5}$$

$$\tan\gamma' = \frac{q_z}{(y_{T_0}{}^2 + x_{T_0}{}^2)^{\frac{1}{2}}} \tag{6}$$

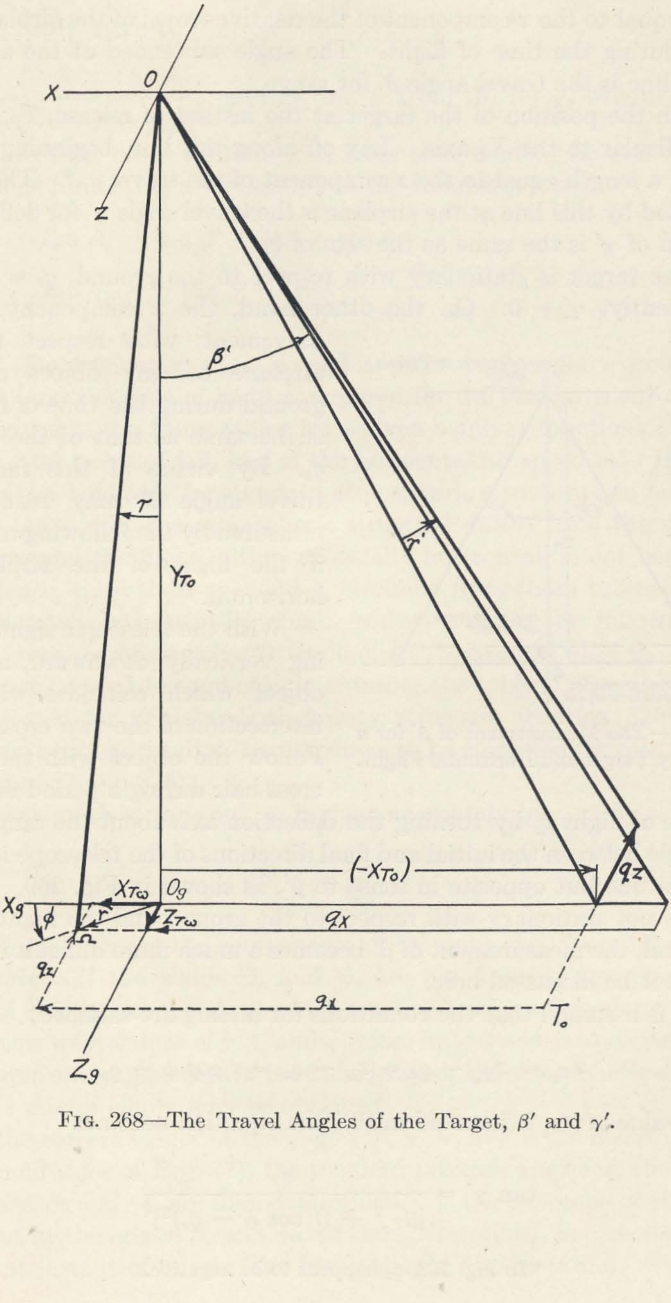


FIG. 268—The Travel Angles of the Target, β' and γ'.

These definitions may also be expressed in words. Lay off on the axis X_g (Fig. 268), beginning at O_g, a line equal in length to q_x or of a length equal to the x component of the relative travel of the airplane and target during the time of flight. The angle subtended at the airplane by this line is the travel angle β' for range.

From the position of the target at the instant of release, T_0, drop a perpendicular to the X_g axis. Lay off along this line, beginning at the X_g axis, a length equal to the z component of the travel q_z.* The angle subtended by this line at the airplane is the travel angle γ' for deflection. The sign of γ' is the same as the sign of q_z.

If the target is stationary with respect to the ground, $q_z = 0$ and, consequently, $\gamma' = 0$. On the other hand, the x component of the movement with respect to the airplane of any object on the ground during the time of flight t_ω is the same as that of the target, q_x. By virtue of this fact, the travel angle β' may readily be measured by the following method, if the flight of the airplane is horizontal.

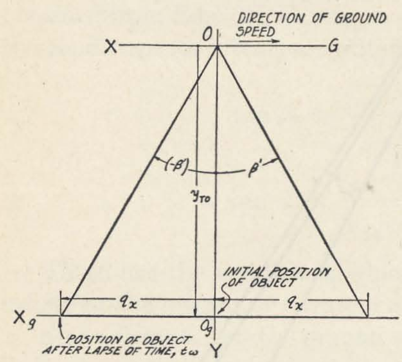


FIG. 269.—The Measurement of β' for a Stationary Target and Horizontal Flight.

With the telescopic sight pointing vertically downward, note an object which coincides with the intersection of the two cross hairs. Follow the object with the range cross hair during a period equal to the time of flight t_ω by turning the deflection axis about the range axis. The angle between the initial and final directions of the telescope is equal in magnitude but opposite in sense to β', as shown in Fig. 269. If the target is not stationary with respect to the ground and the flight is not horizontal, the measurement of β' becomes a much more difficult matter. It will not be discussed here.

If it is assumed that the conditions for hitting are satisfied,

$$x_{T_0} = x_{T_\omega} - q_x = x_\omega - q_x = r \cos \phi - q_x.$$

If this value of x_{T_0} is inserted in (6), the equation becomes

$$\tan \gamma' = \frac{q_z}{[y_{T_0}{}^2 + (r \cos \phi - q_x)^2]^{\frac{1}{2}}} \tag{6'}$$

* In Fig. 268, q_z happens to be negative.

In Eqs. (3), $\tan \beta'$ from Eq. (5) is substituted for $\frac{q_x}{y_{T_0}}$; $\tan \tau$ from (4) for $\frac{r}{y_{T_0}}$; $\tan \gamma'$ from (6′) for

$\frac{q_z}{[y_{T_0}{}^2 + (r \cos \phi - q_x)^2]^{\frac{1}{2}}}$; and $y_{T_0} \tan \beta'$ from (5) for q_x wherever q_x remains after the other substitutions have been made. In this way, the conditions for hitting are obtained in the following form:

$$\begin{aligned} \tan \beta_0 &= \tan \beta' - \tan \tau \cdot \cos \phi \\ \tan \gamma_0 &= -\tan \gamma' + \frac{\tan \tau \cdot \sin \phi}{[1 + (\tan \tau \cdot \cos \phi - \tan \beta')^2]^{\frac{1}{2}}} \end{aligned} \tag{7}$$

317. Determination of τ, ϕ, and t.—The trail angle τ occurring in Eqs. (7) and the time of flight t_ω required for the measurement of β' and γ' are given in the firing tables for a given bomb as functions of y_ω, the depth of the point of fall, and of the horizontal air speed u_h. However, these tables hold only for standard atmospheric structure and horizontal flight. As a rule, the atmospheric structure differs from the standard structure and the flight, although usually horizontal, is not necessarily so. Hence, the values of τ and t_ω obtained from these tables are only approximately correct. To obtain correct values, the following procedure must be observed: (1) the ballistic horizontal wind $\overline{w}_h$ (Section 324) must be used instead of u_h in entering the tables; (2) τ and t_ω must be corrected for non-standard density structure (Section 325); (3) if the flight is not horizontal, τ and t_ω have to be corrected for rate of climb (Sections 321 and 325).

The azimuth of the trail, ϕ, is given accurately by

$$\tan \phi = \frac{\overline{w}_z}{\overline{w}_x}$$

where $\overline{w}_x$ and $\overline{w}_z$ are the components of $\overline{w}_h$ along the X and Z axes, respectively. If the winds $\overline{w}_x$ and $\overline{w}_z$ are not known, an approximate value of ϕ is the drift angle ψ, which is measured at the airplane.

In this way, values of τ, t_ω and ϕ, more or less accurate depending on the degree of completeness of the knowledge of the atmospheric structure and the rate of climb, may be obtained.

If the correct values of the angles β', γ', τ, and ϕ are inserted in the right-hand sides of Eqs. (7), the required position angles at the instant of release, β_0 and γ_0, are then determined. If the telescope of the bomb sight set at the angles β_0 and γ_0, as thus determined, is directed at the target at instant of release, the bomb should hit the target.

318. Aiming the Airplane.—The procedure of aiming the airplane so that the position angles β and γ will have the values β_0 and γ_0, as given by Eqs. (7), at the instant of release is accomplished by the aid of the telescopic sight mounted as described in Section 316. With the angle γ_0 set off on the deflection axis, the plane is so maneuvered that the target comes into view in the telescopic sight, and becomes and is kept aligned with the deflection cross hair.*

As the course is changed to obtain the alignment with the deflection cross hair, the angles ϕ, β', and γ' will change also, and thus for each new tentative course a new value of γ_0 must be computed and set off on the deflection axis. It may be seen that, to obtain a strict solution for γ_0, the values of ϕ, β', and γ' must be measured currently as the course changes, and γ_0 computed and set off currently on the deflection axis. If this is not done and if the course is changed with a given value of γ_0 set off on the deflection axis, then ϕ, β', and γ' must be measured for the new course and a new value γ_0 computed and set off. This will require another change and another measurement of ϕ, β', and γ'.

Hence, unless the measurements and computations can be carried on currently, the correct value of γ_0 and the correct course can be attained only by successive approximations, to complete which one or more preliminary flights over the target are required.

Assuming that the correct course with the correct value of γ_0 has been obtained, that the deflection cross hair is on the target, and that the value of β_0 for the current course has been computed, the range cross hair is now aligned with the target and is made to follow the target by tilting the deflection axis about the range axis. The range axis, in the meantime, must always be kept perpendicular to the track (i.e., aligned with the Z axis). When the tilt of the deflection axis about the

* According to this procedure, γ is kept constant and equal to γ_0, during an approach to a target. But [Eqs. (1)]

$$z_T = (y_T^2 + x_T^2)^{\frac{1}{2}} \tan \gamma.$$

In this equation $(y_T^2 + x_T^2)^{\frac{1}{2}}$ is the distance from the airplane to T_x (Fig. 266), which decreases as the target is approached. If γ is constant, z_T will therefore decrease during an approach. Now z_T is the distance from the target to the vertical plane including the track and, hence, if the course is unchanged, is constant. From this it appears that, if γ is kept constant, the course must change.

To fly an unchanging course, it follows from the above that $\tan \gamma$ should be inversely proportional to $(y_T^2 + x_T^2)^{\frac{1}{2}}$, the distance from the airplane to T_x. Thus γ should be made to approach γ_0 according to the relation,

$$\tan \gamma = \frac{(y_{T_0}^2 + x_{T_0}^2)^{\frac{1}{2}}}{(y_T^2 + x_T^2)^{\frac{1}{2}}} \tan \gamma_0 = \frac{y_{T_0}}{y_T} \frac{(1 + \tan^2 \beta_0)^{\frac{1}{2}}}{(1 + \tan^2 \beta)^{\frac{1}{2}}} \tan \gamma_0$$

if the course is to be kept unchanged.

range axis is such that its angle with the horizontal is β_0, the bomb is released.

319. Special Cases.—In the preceding treatment, no restrictions have been placed on the flight of the airplane except that it should fly in a straight line with constant speed as observed from the earth.

Horizontal Flight.—If the flight is horizontal, values of τ and t_ω calculated on this basis may be inserted in Eqs. (7) to calculate β_0 and γ_0.

Values of τ appearing in these equations, as depending upon the horizontal air speed u_h, which is equivalent to $\bar{w}_h$ for normal air structure, and upon the altitude at release y_{T_0}, which is equal to y_{T_ω} for the horizontal flight here assumed, are given in firing tables or charts, such as Fig. 270. The time of flight t_ω required for the measurement of the travel angles β' and γ' is given in firing tables or charts, such as shown in Fig. 271.

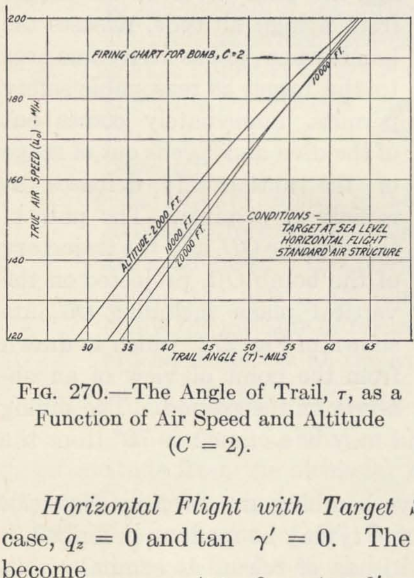


FIG. 270.—The Angle of Trail, τ, as a Function of Air Speed and Altitude ($C = 2$).

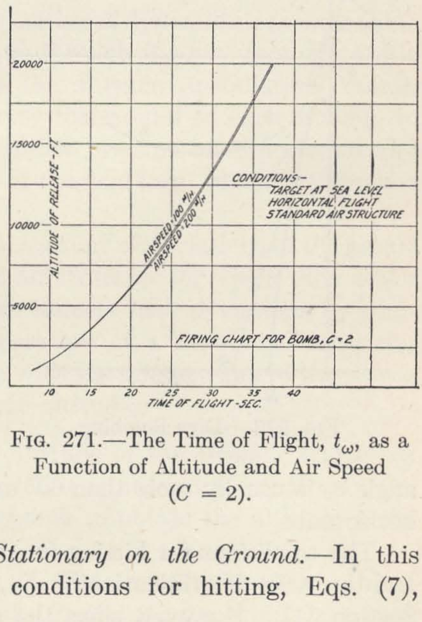


FIG. 271.—The Time of Flight, t_ω, as a Function of Altitude and Air Speed ($C = 2$).

Horizontal Flight with Target Stationary on the Ground.—In this case, $q_z = 0$ and $\tan\ \gamma' = 0$. The conditions for hitting, Eqs. (7), become

$$\begin{aligned} \tan\ \beta_0 &= \tan\beta' - \tan\tau\cos\phi \\ \tan\ \gamma_0 &= \frac{\tan\tau\sin\phi}{[1 + (\tan\tau\cdot\cos\phi - \tan\beta')^2]^{\frac{1}{2}}} \end{aligned} \tag{8}$$

In this case, also, the x component of the motion with respect to the airplane of any object fixed to the ground is the same as that of the target. Hence β' can be measured as explained in Section 316.

Horizontal Flight Down Wind or Up Wind.—If the wind structure is

standard and the direction of the ground speed is up-wind or down-wind, then $\phi = \psi = 0$ (see Fig. 263). For this case, the conditions for hitting, Eqs. (8), become

$$\begin{aligned} \tan \beta_0 &= \tan \beta' - \tan \tau \\ \tan \gamma_0 &= 0. \end{aligned} \tag{9}$$

If the flight is up-wind, the ground speed v_g will be less than when the flight is down-wind. Thus a greater time is available for aiming during an up-wind flight than during a down-wind flight. However, the slower ground speed during an up-wind flight makes the airplane more vulnerable to attack by antiaircraft guns.

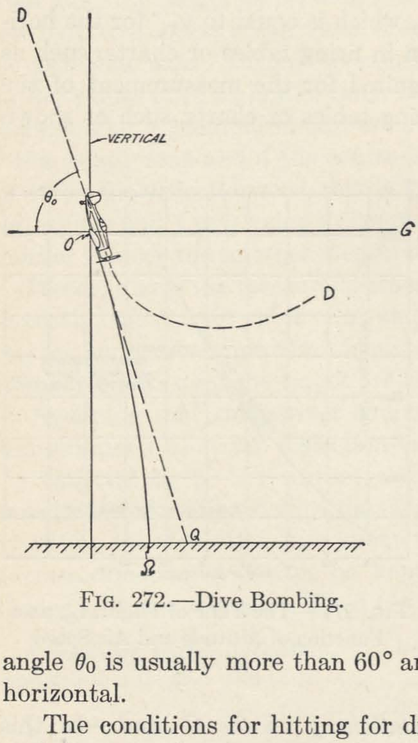


FIG. 272.—Dive Bombing.

Dive Bombing.—In dive bombing, the pilot dives at the target from a high altitude, releases the bomb when he has arrived as near to the target as reasonable safety permits, immediately comes out of the dive and speeds out of range of the antiaircraft defenses as rapidly as possible. The path of the airplane OD, and the trajectory of the bomb $O\Omega$, projected on the vertical plane including OG, are shown in Fig. 272, which is drawn from the point of view of an observer on the ground. The diving angle θ_0 is usually more than 60° and may be as much as 70° from the horizontal.

The conditions for hitting for dive bombing are given by Eqs. (7), and the strict determination of τ, ϕ, and t_ω may be made as described in Section 317. However, since the altitude of release is comparatively low, usually not more than 4000 ft., the air speed relatively high, about 265 miles per hour, and the diving angle high, the trajectory diverges only slightly from the tangent to the trajectory of the bomb at release, OQ. Thus, if the plane is so aimed that the line OQ hits the ground slightly above the target as viewed by an observer on the plane, the bomb should fall near the target. Approximate methods of estimating the angle $\Omega\ OQ$ required to hit the target may be used, but these will not be discussed here.

320. Determination of the Altitude.—One of the arguments upon which the trail angle τ and the time of flight t_ω depend in the firing tables is the depth of the point of fall y_ω, or the altitude at impact y_{T_ω}, which depends upon y_{T_0}, the altitude at release. The altitude at release is determined by means of the altimeter which is carried in the airplane. Since the atmospheric pressure decreases with altitude in a known manner, the altitude may be measured by means of the pressure which obtains at the given altitude. The altimeter is essentially an aneroid barometer whose scale, instead of indicating atmospheric pressure, is graduated to indicate altitude above sea level in an atmosphere of a certain structure defined for altitude measurements.* Such instruments will indicate the altitude with sufficient accuracy when:

a. The instruments, as installed in the airplane, are calibrated to eliminate errors in the instrument itself (instrumental errors) and errors caused by the imposition of dynamic air pressure, due to the motion of the airplane through the air, upon the static air pressure which denotes the altitude (installation errors).

b. They are adjusted before leaving the ground on each mission, to allow for the existing barometric pressure on the ground and the altitude above sea level of the field from which the airplane takes off.

c. Corrections are applied to take account of deviations of the actual structure from the standard air structure for which their scales are graduated. The bomber detects such deviations by comparing the actual air temperature at a number of altitudes below the altitude of release with the temperature of the standard air structure at the same altitudes.

The altimeter gives directly the altitude of the airplane above sea level. If the target is above sea level, it is necessary to subtract the target altitude from the altimeter reading to obtain the altitude of the airplane above the target.

321. Determination of the Rate of Glide or Climb.—The rate of glide or climb can be determined by the climb indicator which is carried in the airplane. This instrument is, in principle, an aneroid barometer which is so constructed that air may leak from the outside to the inside of its bellows through a minute orifice, or vice versa.

Owing to the leak, the air pressure inside the bellows will always be equal to the pressure outside the bellows, regardless of its value, so long as the outside pressure remains constant. When the air pressure outside

* The structure which is standard for altitude measurement differs somewhat from that defined in Section 313.

the bellows is raised or lowered, the pressure inside the bellows will be lower or higher until it can again be equalized by the leakage of air through the orifice. The difference in the air pressure inside and outside the bellows and, consequently, the distention or contraction of the bellows, is dependent on the rate of change of the air pressure outside the bellows. The instrument therefore indicates the rate of change of the atmospheric pressure and, since the atmospheric pressure depends upon the altitude, it indicates, when properly calibrated, the rate of change of altitude, or rate of glide or climb. The indications of this instrument must, of course, be corrected for instrumental and installation errors and also to take account of the effect of air density which varies with altitude.

322. Determination of the Air Speed.—The horizontal air speed of the airplane at the instant of release u_h is given by the air speed indicator, provided the flight is horizontal. If not, its indications must be corrected for rate of glide or climb. The operation of the air-speed indicator depends upon the principle of the Pitot tube, that is, it measures the difference between the static air pressure and the dynamic air pressure caused by the motion of the airplane through the air. The dynamic air pressure is approximately proportional to ρu^2, where ρ is the density of the air and u is the air speed. To make the indications of these instruments sufficiently accurate to be useful for precision bombing, it is necessary that:

a. The instruments, as installed in the airplane, be calibrated for air of standard density at sea level, ρ_0, to eliminate the instrumental and installation errors.

b. The indications of the calibrated instrument (calibrated indicated air speed) be corrected for the effect of the decrease of the density of the air with altitude, to obtain the true air speed. This correction is made by multiplying the calibrated indicated air speed by a factor which is a function of the altitude.

323. Bomb Sights.—The principal functions of a bomb sight are to provide for measuring the travel angles β' and γ', and the drift angle ψ, and for establishing the line of sight OT_0 as determined by the position angles β_0 and γ_0. For this purpose it contains a telescopic sight mounted so that it can be oriented in the manner described schematically in Section 315.

Since the angles β' and β_0 are measured from the vertical, and γ' and γ_0 from a vertical plane, whereas the angle ψ is measured in a horizontal plane, a bomb sight must also include a means for establishing a vertical line or, what will serve the same purpose, a horizontal plane. In the

earlier types of bomb sights, pendulums and bubble levels were used for this purpose. They are, however, unsatisfactory since they are affected by the accelerating forces created by changes in the speed of the airplane.

After the position angles β_0 and γ_0 have been determined, the pilot must fly the airplane on a course such that when the position angle of the target for range is β_0, its position angle for deflection will be γ_0. A good bomb sight will therefore include a means for indicating to the pilot the course he should fly.

It was shown in Section 318 that one consequence of the adjustment of the course of the airplane during the approach to the target was a change in the angles ψ, β', γ', β_0, and γ_0. If high precision in bombing is to be attained, these changes must be taken into account. The time available for making new observations of the angles ψ, β', and γ', and for recomputing the angles β_0 and γ_0, is so short that these operations can be accomplished only if they are carried out automatically. This suggests a mechanical solution of the equations involved. The bomb sights used in the different countries vary greatly in details of construction and in the completeness with which they are able to solve the problems involved. The usefulness of the simpler types is limited to one or more of the special conditions cited in Section 319, whereas the more elaborate types impose fewer restrictions in this respect.

324. The Ballistic Range and Cross Winds.—According to the definition of standard wind structure given in Section 313,

$$w_x(y) = u_h \cos \psi, \quad w_z(y) = u_h \sin \psi \tag{10}$$

If the relations (10) hold, the wind is constant in magnitude and direction, the trail angle τ and the time of flight t_ω may be computed from the air speed u_h, and the azimuth of the trail ϕ is given by $\phi = \psi$. As a rule, however, the wind varies in direction and magnitude as a function of the depth of the target, y. In this case, a method is needed for the computation of τ, t_ω, and ϕ.

For this purpose, ballistic winds (see Section 297 of Chapter X) are defined in the following table.

Symbol	Definition
$\overline{w}_x$	The constant range wind, independent of y, which produces the same range component of the trail, $r \cos \phi$, as the actual range wind, $w_x(y)$.
$\overline{w}_z$	The constant cross wind which produces the same deflection component of the trail, $r \sin \phi$, as the actual cross wind, $w_z(y)$.
$\overline{w}_h$	The constant resultant horizontal wind which produces the same trail r as the actual resultant horizontal wind $w_h(y)$. $\overline{w}_h$ is given by $\overline{w}_h^2 = \overline{w}_x^2 + \overline{w}_z^2$. (11)

If the values of $r \cos \phi$ and $r \sin \phi$ are assumed to be proportional to the winds that produce them, $\bar{w}_x$ and $\bar{w}_z$, then

$$\frac{\bar{w}_z}{\bar{w}_x} = \frac{r \sin \phi}{r \cos \phi} = \tan \phi \tag{12}$$

Thus the azimuth of the trail is determined if $\bar{w}_x$ and $\bar{w}_z$ are known.

Since $\bar{w}_h$ is a constant horizontal wind, it will produce the same trail and, hence, the same trail angle τ as an air speed u_h of the same magnitude. As has been explained, u_h is equivalent to a constant horizontal wind w_h. Hence, if $\bar{w}_h$ is known, the trail angle τ and the time of flight t_ω* can be obtained from the firing tables or charts, such as those shown in Figs. 270 and 271, by entering them not with u_h, the horizontal air speed, but with $\bar{w}_h$ instead; or, in the tables, τ and t_ω could be given not as functions of u_h but of $\bar{w}_h$.

The determination of the ballistic range and cross winds for the varying air speeds and altitudes at which the airplane may fly is complicated in practice, because it is not feasible for an observer moving with the reference frame, or with the airplane, to measure the winds with respect to the reference frame at all points of the trajectory. If the air at all points of the trajectory has the same speed and direction with respect to the ground as the air at the level of the airplane, then the speed and direction of the air with respect to the reference frame moving with the airplane will also be constant, and the standard air structure, Eq. (10), holds. A variation from standard air structure, therefore, involves differences between the wind, as measured from the ground, at the level of the airplane, and the winds at other points of the trajectory. Properly weighted average values of these differences should provide a basis by means of which the air speed u_h may be corrected to obtain the ballistic horizontal wind $\bar{w}_h$. Thus the method of obtaining $\bar{w}_h$, to be described, involves measurements of the differences between the wind at the airplane and the winds at the other points of the trajectory.

Let the components of the wind, measured with *respect to the ground* as a function of the altitude s above the target, be

$$w_N(s) \text{ and } w_E(s)$$

where $w_N(s)$ is the component of the wind velocity towards the north and $w_E(s)$ the component towards the east. It is assumed that these winds are measured by a suitably placed meteorological station.

* If $\bar{w}_h$ is computed to give τ correctly, it will give t_ω approximately; or, if computed to give t_ω correctly, it will give τ approximately. However, these approximations will probably be satisfactory for most purposes.

Let the altitude of the airplane above the target be p. Hence, p is numerically equal to y_T. Now form the differences between the wind components at the airplane and their values at any other altitude s:

$$[w_N(s) - w_N(p)], \quad [w_E(s) - w_E(p)]$$

where $w_N(p)$ and $w_E(p)$ are the wind components, measured with respect to the ground, at the altitude of the airplane. These differences are designated by w_{pN} and w_{pE}, respectively, and denote the wind velocity as measured in a *reference frame moving with the air*, not the airplane, at the level of the airplane.

Mean values of w_{pN} and w_{pE} from the level of the target up to the altitude of the airplane p, using the proper weighting factors, are now obtained and designated by

$$\overline{w}_{pN} \text{ and } \overline{w}_{pE}.$$

These are ballistic winds defined with reference to the air at the level of the airplane. It is to be noted that if the wind components $w_N(s)$ and $w_E(s)$ are constant, i.e., independent of s, $\overline{w}_{pN}$ and $\overline{w}_{pE}$ are zero. The resultant horizontal ballistic wind $\overline{w}_p$, defined with reference to coordinates moving with the air at the level of the airplane, is given by the relation,

$$\overline{w}_p{}^2 = \overline{w}_{pN}{}^2 + \overline{w}_{pE}{}^2.$$

The azimuth α, of $\overline{w}_p$, measured from the north towards the east, is determined by the relations,

$$\sin \alpha = \frac{\overline{w}_{pE}}{\overline{w}_p}, \qquad \cos \alpha = \frac{\overline{w}_{pN}}{\overline{w}_p},$$

as may be seen from Fig. 273.

Let the azimuth, with respect to the north, of the X axis of the reference frame moving with the airplane be λ, which may be determined from the azimuth of the course OA and the drift angle ψ, Fig. 262. Then, the components of the wind $\overline{w}_p$ along the X and Z axes, designated by $\overline{w}_{px}$ and $\overline{w}_{pz}$, respectively, are given by

$$\overline{w}_{px} = \overline{w}_p \cos(\lambda - \alpha), \qquad \overline{w}_{pz} = \pm\, \overline{w}_p \sin(\lambda - \alpha) \tag{13}$$

If the Z axis points to the left of an observer looking along the X axis, the positive sign is to be taken in the latter of Eqs. (13).

The x component of the motion of the air at the airplane, with respect to the airplane, is $u_h \cos \psi$, whereas the x component of the weighted average or ballistic velocity of the air along the trajectory, with respect to air at the airplane, is $\overline{w}_{px}$. Thus, the x component of the ballistic

velocity of the air along the trajectory, with respect to the airplane or the chosen reference frame, is the sum of $u_h \cos \psi$ and $\overline{w}_{px}$. This sum is called the ballistic range wind and is designated by $\overline{w}_x$. In a similar manner, the ballistic cross wind $\overline{w}_z$ may be shown to be equal to $u_h \sin \psi \pm \overline{w}_{pz}$. Therefore

$$\overline{w}_x = u_h \cos \psi + \overline{w}_p \cos (\lambda - \alpha)$$

$$\overline{w}_z = u_h \sin \psi \pm \overline{w}_p \sin (\lambda - \alpha).$$

From these, the ballistic horizontal wind $\overline{w}_h$ with reference to the coordinates moving with the airplane, may be computed by Eq. (11), and the azimuth of the trail ϕ by Eq. (12).

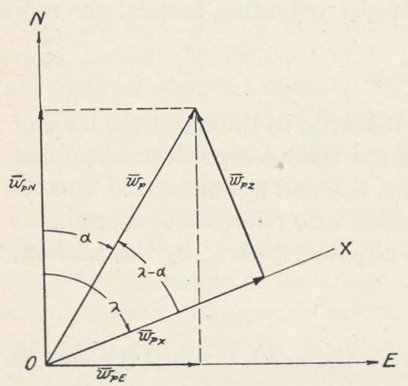


FIG. 273.—Wind Component Chart.

The ballistic horizontal wind $\overline{w}_h$ may be regarded as a value of u_h corrected for non-standard wind structure. If the firing tables have u_h as an argument, $\overline{w}_h$, if known, should be used instead in entering the tables, or the tables may use $\overline{w}_h$ as an argument instead of u_h.

It is evident that the weighting factors used in the computation of the ballistic winds $\overline{w}_{pN}$ and $\overline{w}_{pE}$, measured with reference to the air at the airplane, should be such as to make $\overline{w}_x$ and $\overline{w}_z$ satisfy the requirements of their definitions. The general methods of computing the ballistic wind are given in Section 297 of Chapter X.

If the ballistic range and cross winds $\overline{w}_x$ and $\overline{w}_z$ are known, the trail angle τ and the time of flight t_ω may be obtained from the firing tables, and the azimuth of the trail ϕ can be computed. However, this procedure is likely to be of little practical value if the target is far removed from the meteorological station by which the ballistic winds $\overline{w}_{pN}$ and $\overline{w}_{pE}$ are measured, since the wind velocity and direction vary considerably from place to place at a given instant. Thus, unless a method is developed by which the bomber himself may measure the ballistic winds, the use of the ballistic horizontal wind $\overline{w}_h$ in place of the air speed u_h would hardly be justified. In default of such a method, the current practice is to use the value of u_h given by the air-speed indicator, although the practice may lead to serious errors since the difference

between u_h and $\overline{w}_h$ is frequently quite large, and produces an important effect on τ.

325. Differential Effects.—In computing firing charts, Figs. 270 and 271, giving the trail angle τ and the time of flight t_ω for a certain bomb as function of air speed u_h and altitude at release y_{T_0}, certain conditions which affect the trajectory of the bomb have been assumed. These are known as firing-table conditions and are listed below:

(*a*) The air structure is standard in regard to density and temperature.

(*b*) The rate of climb is zero, or the flight is horizontal.

(*c*) All bombs of a given type have the same ballistic coefficient.

The effect of a variation from any of the standard firing-table conditions listed above is to *change the trail angle* τ *and the time of flight* t_ω by appreciable amounts. Hence, if the greatest precision is to be obtained, the effects of such variations must be listed in the firing tables and corrections made for them when the bomb is dropped; since, in practice, the firing-table conditions almost never hold. Methods of computing the effects of such variations are given in Section 296 of Chapter X.

If corrections for the non-standard conditions are to be made,* the amounts of the variations from the standard conditions must be measured, unless already known.

(*a*) The ballistic density might be obtained from the meteorological station which provides such measurements for the artillery, provided the target is not too far removed from the station. The standard density is given by $\rho = \rho_0 e^{-h(y_\omega - y)}$. The difference between the ballistic density and the standard density, in percentage, gives the required measure of the variation in the density structure from standard. The standard density structure assumes that the density at the point of fall, $\rho(y_\omega)$, is equal to ρ_0. If the altitude of the target above sea level is considerable, the difference between ρ_0 and $\rho(y_\omega)$ will be appreciable and, in the absence of meteorological data, may be estimated simply from the known altitude of the target. The ratio $\dfrac{\rho(y_\omega) - \rho_0}{\rho_0}$ is then an approximate value of the variation of the density structure from standard.

* As was pointed out in Section 324, it is customary to neglect the difference between the horizontal air speed u_h and the horizontal ballistic wind $\overline{w}_h$. The effect on the trail angle τ of the difference between u_h and $\overline{w}_h$ may be appreciable. Errors of considerable magnitude in measuring the altitude, air speed, and the travel angles β' and γ' also occur. In view of the neglect of the difference between u_h and $\overline{w}_h$ and of the presence of the errors mentioned, in the technique of bombing as now applied no attempt is made to correct for the other variations from the standard conditions listed in this Section, unless they are of considerable magnitude.

The effect of a non-standard temperature structure on the trajectory is small and probably may be safely neglected.

(*b*) The rate of climb may be obtained from the climb indicator and corrections made if the rate of climb is not zero. A rate of climb affects τ and t_ω in three different ways:

(1) Assuming that the vertical wind with respect to the ground is zero, it produces a vertical wind w_y, which affects τ and t_ω.

(2) Since the trail, r, depends upon the depth of the point of fall, y_ω, or the altitude at impact, y_{T_ω}, and τ is defined by

$$\tan \tau = \frac{r}{y_{T_0}}$$

where y_{T_0} is the altitude at release; therefore, if the rate of climb is not zero, $y_\omega \neq y_{T_0}$, and account must be taken of the difference between y_ω and y_{T_0}.

(3) The time of flight t_ω will depend upon y_ω and not upon y_{T_0}.

(*c*) An attempt is made to keep the ballistic coefficient C the same for all bombs of a given type. However, on account of unavoidable variations in weight, size, and shape, an appreciable variation in C may occur. The variation in C due to the variation in size and weight from the standard size and weight may be easily computed, as indicated in Section 289, Chapter X. However, it is difficult to allow for the effects of variations in the shape, especially of the fin assemblies.

CHAPTER XIII

OFF-CARRIAGE FIRE-CONTROL INSTRUMENTS

The designation of *off-carriage fire-control instrument* includes all fire-control instruments which are not mounted on gun carriages. These instruments supply the data to be set off on the sights, drums, quadrants, and other aiming and laying devices mentioned in a preceding chapter. The determination of the data and the control of artillery fire on *terrestrial* targets involves three distinct steps, namely:

a. Range and position finding.
b. Range and deflection correction.
c. Spotting and adjustment.

326. Range and Position Finding.—*Range and position finding* may be defined as the determination of the actual range and direction of the target from the directing point of the battery. For moving targets this includes the prediction of the *set forward point,* which is the predicted future position of the target at the instant the projectile is expected to arrive.

Ranges and positions are determined by several methods, all of which depend essentially upon measurement of distances and angles and upon the solution of triangles having the target at an apex. Terrestrial observation, balloon observation, airplane observation, aerial photographs, sound ranging, and flash ranging are some of the methods used to locate the position of the target with respect to the ends of a measured base line, or the directing point of the battery.

Three systems of range and position finding in general use are described below.

a. The horizontal base system requires a station, equipped with an azimuth reading instrument, at each end of a measured horizontal base line.

Figure 274 shows the horizontal base system triangles. AB represents the measured base line, C the target, and X the directing point of the battery. YX is drawn perpendicular to the base line.

In the triangle, ABC, the distance AB is known, and the angles CAB and ABC are determined by direct instrumental measurement. The distances YX, XB, and YB are measured, and the angle BYX is a right angle. From these values, the distance BC and the angle XBY may be determined mathematically; then, in the triangle XBC, the distance XC and the angles XBC and CXB may be calculated.

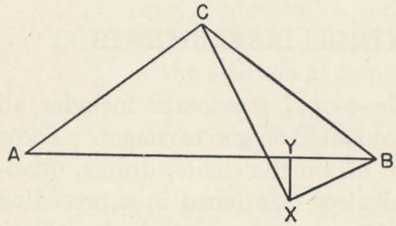


Fig. 274.

It is evident that the necessity for speed in the determination of firing data precludes the use of the slow process of trigonometric calculation. Normally, the problem is solved mechanically and graphically by means of a plotting board or other plotting equipment.

b. The vertical base system requires a single station equipped with a depression position finder. This system involves the solution of a vertical right triangle. One leg of the triangle is represented by the height of the position finder above the horizontal plane through the target, parallel to the datum plane of mean low water at the instrument; the other leg is represented by the horizontal distance of the target from the observing instrument; and the hypotenuse is represented by the line of sight of the instrument.

Figure 275 shows the basic triangle for the vertical base system. O represents the position of the depression position finder and T the position of the target.

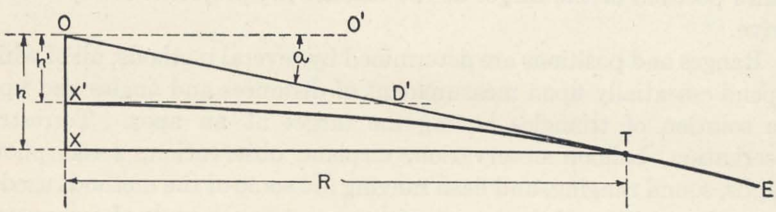


Fig. 275.

$X'TE$ represents the surface of the sea, $X'D'$ (horizontal) the datum plane of mean low water at the instrument, and XT a plane through T parallel to the datum plane of mean low water. OT is the line of sight intersecting the datum plane of mean low water at D', angle a is the depression angle measured at O, h is the vertical distance of O above the datum plane of the target, h' the height of O above the datum plane of mean low water, and $h - h'$ the projection of the curvature of the earth in feet for the range $XT = R$.

Since OO' is parallel to XT, the angle XTO is equal to the measured angle a. Then, knowing a and h, the other elements of the triangle XTO may be determined.

The difference between h' and h is a function of the curvature of the earth and the range R. The distance h varies with the tide, and the line of sight is subjected to curvature because of refraction. The corrections for these effects give a corrected triangle which can be solved. However, it would be impracticable to go through the calculations necessary to apply the corrections to each observation. The depression position finder solves the problem mechanically, indicating the corrected horizontal range and azimuth of the target.

c. The self-contained horizontal base system requires a single station equipped with a self-contained horizontal-base range finder. If the range finder is not equipped for reading azimuths, an azimuth reading instrument is also required. This system involves the solution of a

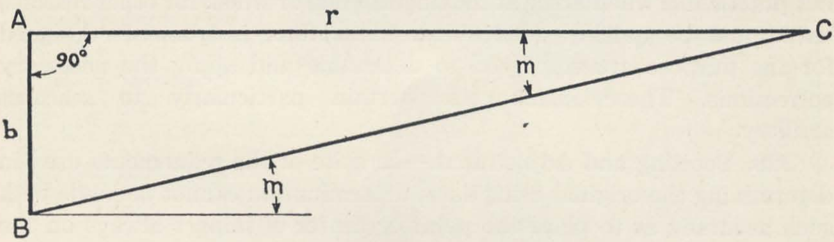


FIG. 276

horizontal right triangle. The range finder contains the base of the triangle and a means of measuring the complement of the adjacent acute angle.

The basic triangle for the range finder is shown in Fig. 276. AB is the base of length b, C the target, and AC the range r. In the usual construction, the base length and angle at A are maintained constant in value. Then $r = \dfrac{b}{\tan m}$ or, since b is constant and m is a small angle, the range is inversely proportional to the angle m. The scale upon which angle m is read is graduated to read in linear units.

All the systems described above are employed by seacoast artillery and, in this connection, generally furnish data to a plotting board where the course of the target is plotted and future positions predicted. *The horizontal base system* is generally standard. *The vertical base system*

does not require as much equipment, and it is used where high locations are possible, or as an alternate with a horizontal base system. *The self-contained horizontal base system* is used principally by rapid-fire batteries (6-in. and smaller), and frequently as an emergency alternative by larger batteries. This system is also used by the field artillery and by troops equipped with infantry weapons.

327. Range and Deflection Correction.—Having determined the actual range and azimuth of the target or set forward point, it is still necessary to consider the various factors which influence the flight of the projectile through the air, such as, the density of the air, wind direction and velocity, rotation of the earth, and predetermined variations of other conditions from normal. *Range and deflection correction* is then defined as the determination and application of position, matériel, and weather corrections for deviations of existing conditions from those assumed as standard in the firing tables.

These corrections may be calculated from the firing tables, but this is not practicable when firing at moving targets, or when, for other reasons, data must be quickly determined. Therefore, instruments designed for the purpose are employed to determine and apply the necessary corrections. These instruments pertain particularly to seacoast artillery.

328. Spotting and Adjustment.—In spite of the refinements used in determining the original firing data, determination cannot be made with such accuracy as to place the point or center of impact always on the target. Thus arises the necessity for *spotting and adjustment.*

Spotting is the process of locating the position of the points of impact with respect to the target or adjusting point. Spotting may be conducted by observation from terrestrial stations or from aircraft. The use of terrestrial stations is the normal method.

In *bilateral spotting,* two stations some distance apart are used, and the angular deviation of the point of impact is read on a suitable instrument at each station. From these angular deviations, the range and direction deviations are determined graphically. A spotting board which facilitates this determination is used by seacoast artillery.

Where only one station is used, the spotting system is called *axial* if the target angle is less than 100 mils, *lateral* if between 100 and 1300 mils, and *flank* if over 1300 mils. Generally, in these systems, only sensings are attempted, i.e., whether the points of impact are over or short, right or left, with respect to the target. Spotting by sensing is also the normal method used with aerial observation.

After the range and deflection deviations of the point of impact from the target have been determined, the necessary range and azimuth cor-

rections are calculated and applied. In this phase, called *adjustment*, the object is to place the center of impact on the target. Adjustment charts and boards are commonly used for the determination of corrections.

329. Azimuth Instrument.—The Azimuth Instrument, Model of 1918, is shown in Fig. 277. It is used principally by heavy and medium caliber mobile artillery as a base-end observing instrument and as a

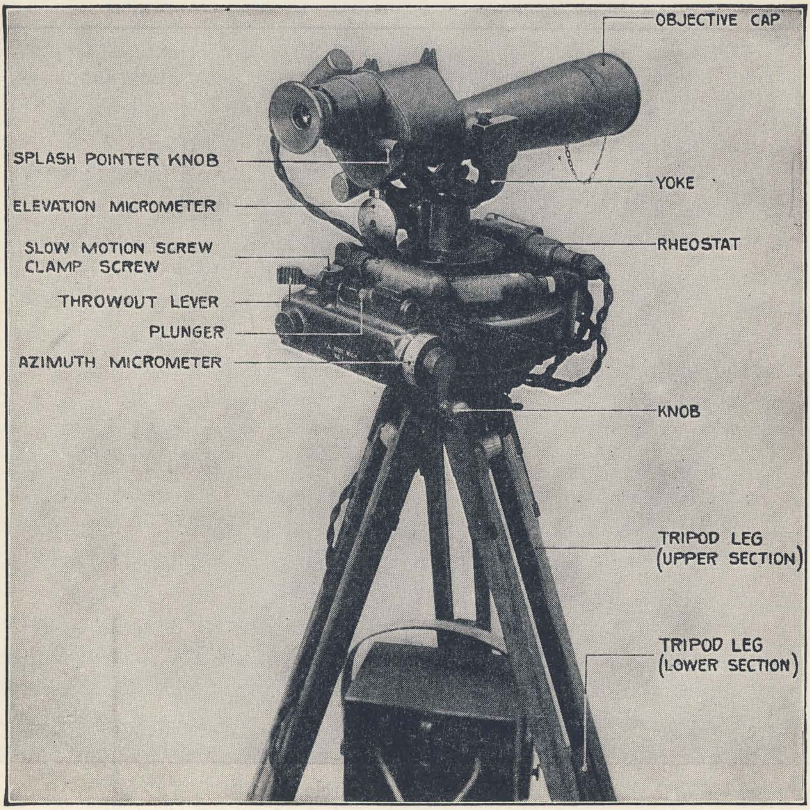


FIG. 277.—Azimuth Instrument, Model of 1918.

spotting instrument. It is designed primarily for accurate measurement of azimuths.

The telescope is equipped with 10- and 20-power eyepieces, the respective fields of view being 4° and 2.5°. The reticle contains horizontal and vertical cross lines. Below the horizontal cross line is a deflection scale, graduated in 5-mil divisions, for use in connection with a movable splash pointer.

The base provides a means for holding the telescope. It contains elevating, traversing, and leveling mechanisms. The elevating mechanism permits measurement of vertical angles from −300 to +500 mils. The least reading on the elevation micrometer is 0.2 mil. The traversing mechanism provides for complete rotation. For rapid changes in azimuth the worm and worm gear are disengaged by means of a throw-out lever. The least reading on the azimuth micrometer is 0.1 mil.

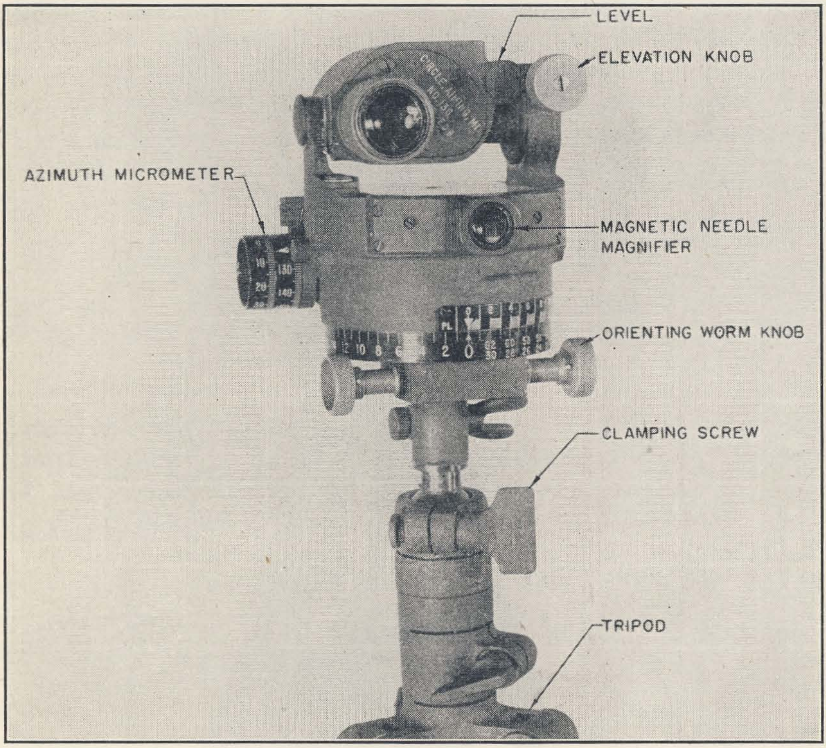


FIG. 278.—Aiming Circle, M1.

The Azimuth Instrument, Model 1910A1, similar except that it is graduated in degrees, is ordinarily used by fixed seacoast artillery.

330. Aiming Circle.—Figure 278 shows the Aiming Circle, M1. It is used by medium and light mobile artillery as a means of measuring angles in azimuth and site and for general topographical work.

The telescope has 4-power magnification and a field of view of 10°. The reticle contains a vertical mil scale and a stadia scale, the former

graduated in 5-mil divisions, 100 mils above and below the normal line, and the latter graduated on the basis of a rod 2 meters in length. These scales are used in measuring distances and angles of site.

The base contains elevating and traversing mechanisms, a leveling device, and a magnetic needle. The elevating mechanism permits rotation of the line of sight 8° above and below the horizontal position. The traversing mechanism permits complete rotation. The azimuth scale is graduated into 64 equal spaces, each representing 100 mils. The upper scale, a plateau scale, is used in conjunction with the sight graduations on the French Collimating Sight, Model of 1901. The least reading on the azimuth micrometer is 1 mil.

The declination for any given locality is determined with this instrument by taking magnetic bearings of several points whose true azimuths can be determined from the map. The difference between each of the magnetic bearings and the corresponding true azimuth is computed. The average of the differences is the declination for the instrument at that locality.

331. Battery Commander's Telescope.—The Battery Commander's Telescope, Model of 1915, shown in Fig. 279, is a binocular observation instrument equipped with means for measuring vertical and horizontal angles. It is used by medium and light mobile artillery and, although designed primarily for spotting and observing the effect of fire, it is frequently used in connection with range and position finding.

Both telescopes, containing similar optical systems (Fig. 280), are mounted on a common pivot and may be rotated laterally from the vertical to a horizontal position. When the telescopes are in the vertical position, the objective prisms are approximately 12 in. above the eyepieces, which facilitates concealment of the observer; with the telescopes in the horizontal position, greater definition to objects in the field of view is obtained. The right-hand telescope contains a reticle bearing horizontal and vertical cross lines and a deflection scale. The instrument has 10-power magnification and a field of view of 4° 15′.

The *angle-of-site mechanism* permits measurement of vertical angles from −300 to +300 mils. The angle of site scale is graduated into 6 equal spaces each representing 100 mils. The 3 graduation is the normal position. The least reading on the angle of site micrometer is 1 mil.

The *azimuth mechanism* provides for complete rotation and the azimuth scale is graduated every 100 mils. The least reading on the azimuth micrometer is 1 mil.

The mount is attached to the tripod by means of a ball-and-socket joint which, with a spherical level, serves as a means for leveling.

332. Depression Position Finder.—Figure 281 shows the Depression Position Finder, M1. This instrument is used by fixed seacoast artillery as a vertical base instrument for the direct measurement of azimuths and for the mechanical computation of horizontal ranges. It is

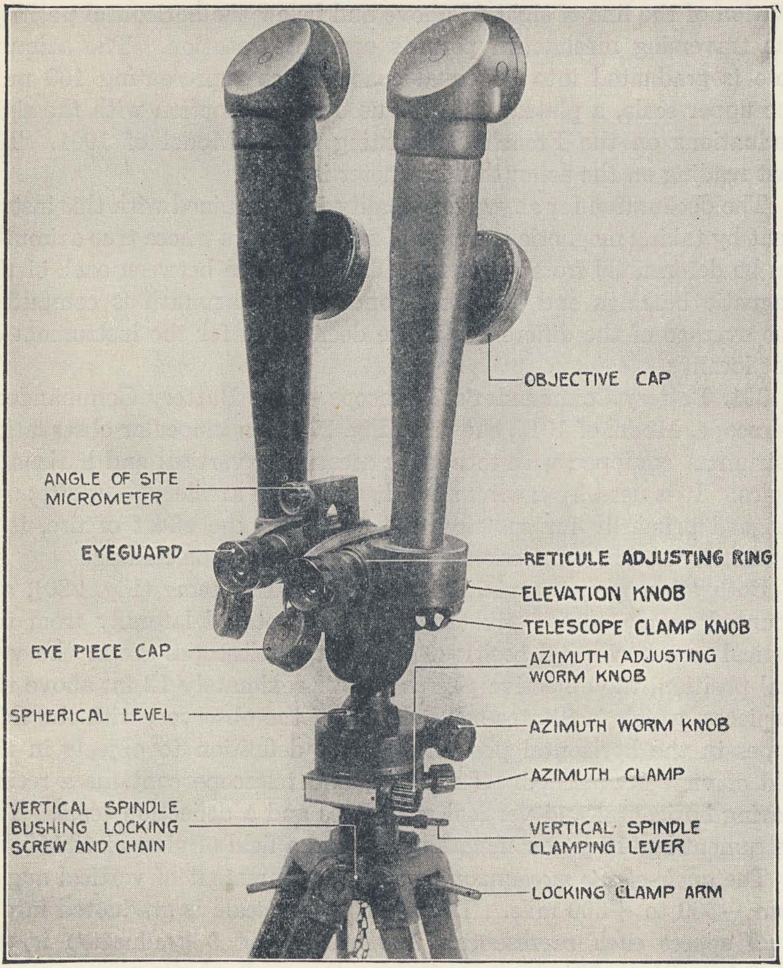


FIG. 279.—Battery Commander's Telescope, Model of 1915.

designed for permanent mounting at known heights of from 75 to 900 ft. above mean low water.

An adjustable power eyepiece on the telescope permits adjustment between 10 and 30 power with corresponding fields of view between 6° 9′

and 2° 3′. The telescope contains horizontal and vertical cross wires.

The mount is accurately leveled on the pedestal by means of four leveling screws. The height above mean low water, and the tide,

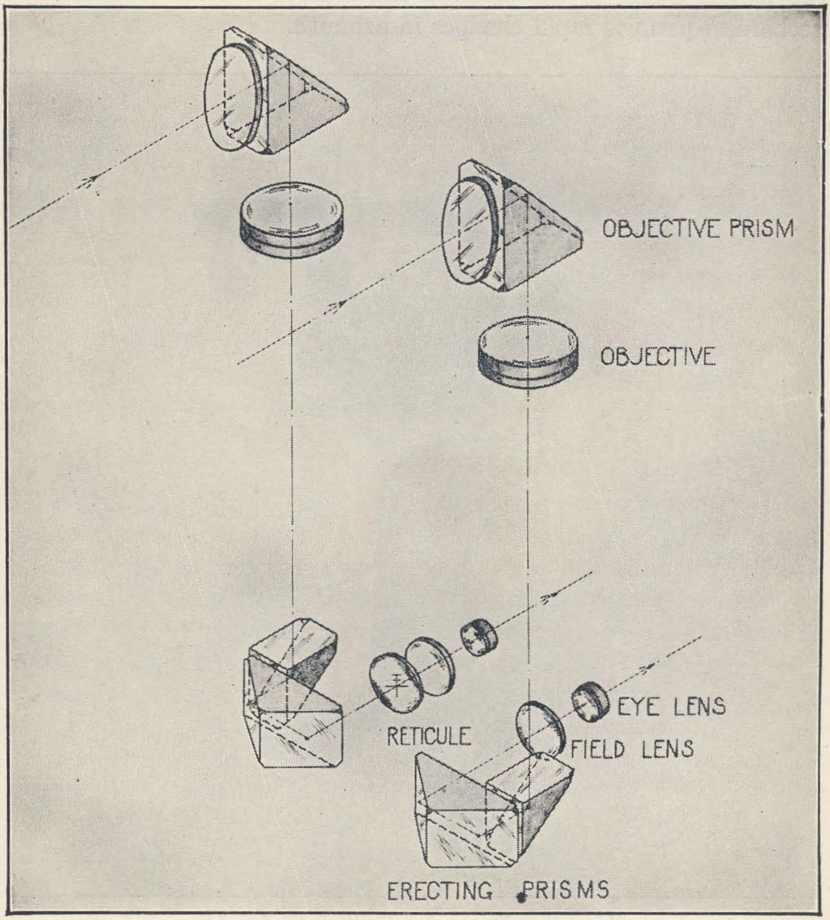


FIG. 280.—Telescopic System of B. C. Telescope.

curvature, and refraction corrections are all set into the instrument by movement of the compensating screw and nut.

In measuring range, the horizontal cross wire is placed on the water line of the target by rotation of the range handwheel, which elevates and depresses the telescope. The tangent of the depression angle is mechanically measured, and the corresponding horizontal range read

directly from a range scale graduated in yards. Ranges from 1500 to 60,000 yd. may be read. The maximum range depends upon the height of the instrument and upon visibility.

Azimuths are read directly from the azimuth circle and micrometer. The least reading of the azimuth micrometer is 0.01°. A throwout mechanism permits rapid changes in azimuth.

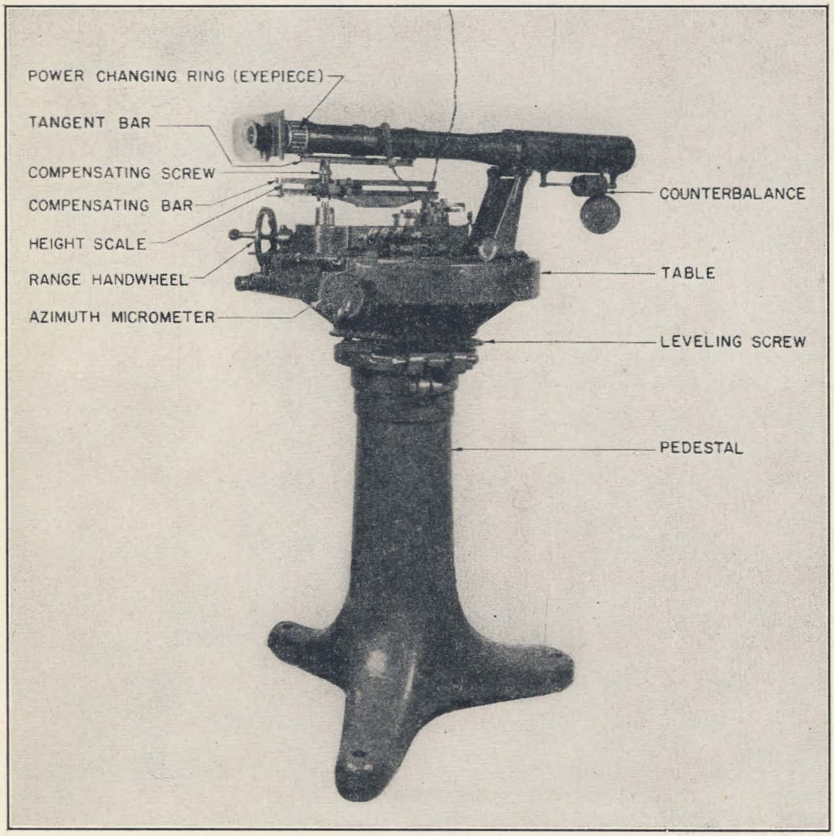


FIG. 281.—Depression Position Finder, M1.

333. Self-contained Horizontal-base Range Finders.—Self-contained horizontal-base range finders are designed for direct measurement of ranges. The principle of operation of a *coincidence-type range finder* is as follows (Fig. 282).

B_L and B_R are two penta prisms at the ends of a base line. O_L and O_R are two objectives. W_F and W_M are two identical wedge prisms of very small angle mounted in inverted positions. W_F is fixed and W_M

is movable. Assume that the focal plane of the eyepiece is perpendicular to the base line at its center M.

If the range finder is directed at an infinitely distant point, the rays of light from that point entering B_L and B_R will be parallel. They will be reflected by B_L and B_R at right angles along the axis of the instrument, and the image formed by each ray will be in coincidence at M in the focal plane. This will be true only if W_F and W_M are in the closed or infinity position, for in this position, since the exterior surfaces of W_F and W_M are parallel, light rays will pass through without refraction.

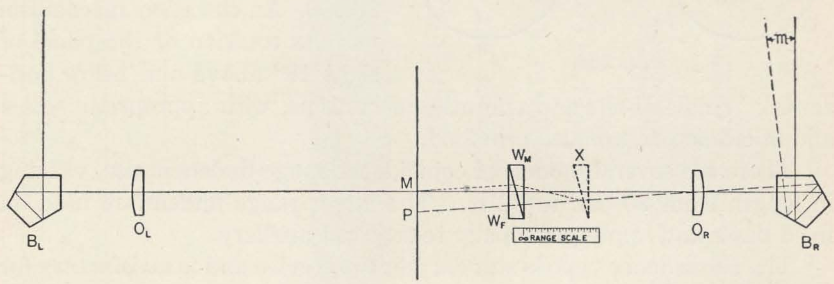


FIG. 282.

Now, if the range finder is directed at a point within its working range, the rays entering B_L and B_R will not be parallel. If the instrument is turned so that the image formed by the ray through B_L is at M as before, the image formed by the ray through B_R will be at some such position as P, or out of coincidence. The displacement is a function of the angle m, which is, in turn, inversely proportional to the range.

The image formed by the ray through B_R is brought into coincidence at M by moving W_M to position X. Each of the wedges in the open position refracts the light ray by an equal amount; W_M refracts upwards and W_F down. The distance through which W_M is moved from its infinity position is proportioned to the angle m, and is a measure of the range which may be read from a suitable scale.

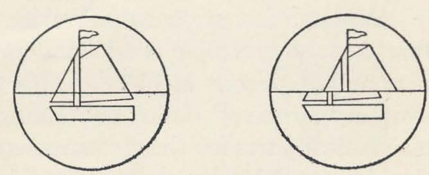


FIG. 283.

Actually, in an instrument, the rays after passing through W_F and O_L are reflected by a specially constructed ocular prism to the focal plane of a single eyepiece. The field in the focal plane is divided by a sharp horizontal line; the partial image in the lower half of the field is that produced by rays through B_L, whereas that in the upper half is formed by rays through B_R. Figure 283 shows the partial images in and out of

coincidence. In some coincidence range finders the images are inverted as shown in Fig. 284. This arrangement is desirable when objects are clearly defined against the sky.

Figure 285 shows the 1-meter base Range Finder, Model of 1916, used by the Infantry, Field Artillery, and Cavalry. It is of the coincidence type, having 15-power magnification and a field of view of 3° 10′. The range scale is graduated in yards from 400 to 20,000. An elevation mechanism permits rotation of the plane of sight 18° above and below horizontal. Angle-of-site and azimuth mechanisms, with appropriate scales and micrometers, are also provided.

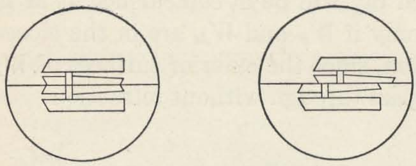


FIG. 284.

There are several models of coincidence range finders in use, varying in length from 80 cm. to 30 ft. The larger range finders are used on fixed bases and apply principally to seacoast artillery.

The coincidence type is standard in the service and is satisfactory for determining ranges to fixed or slowly moving targets. However, coincidence on fast-moving targets is hard to obtain, and on such targets stereoscopic range finders may be used more effectively.

The *stereoscopic range finder* differs fundamentally from the coincidence range finder in that it is a binocular instrument and in that its operation depends upon stereoscopic vision, or the power of depth perception. With the unaided eye the absolute limit of stereoscopic vision is approximately 480 yd. but this limit may be extended by lengthening the effective distance between the two points from which the observer views the object, and by magnification.

When two objects are observed simultaneously, stereoscopic vision enables an observer to judge with considerable accuracy the *relative* distances to the two objects. This, rather than the estimation of actual distances, is the basis of stereoscopic range finding.

Although few stereoscopic range finders are used by the service at this time, stereoscopic height finders are being used in increasing numbers by antiaircraft artillery. This type of height finder is in reality a stereoscopic range finder containing additional optical elements and mechanical parts for the measurement of altitudes. A detailed description is given in the chapter on fire control for antiaircraft artillery.

334. Plotting Board.—A plotting board is a position finding instrument used principally by seacoast artillery. It is employed with all three systems of range and position finding.

The field of fire of the battery and all elements of the position-finding

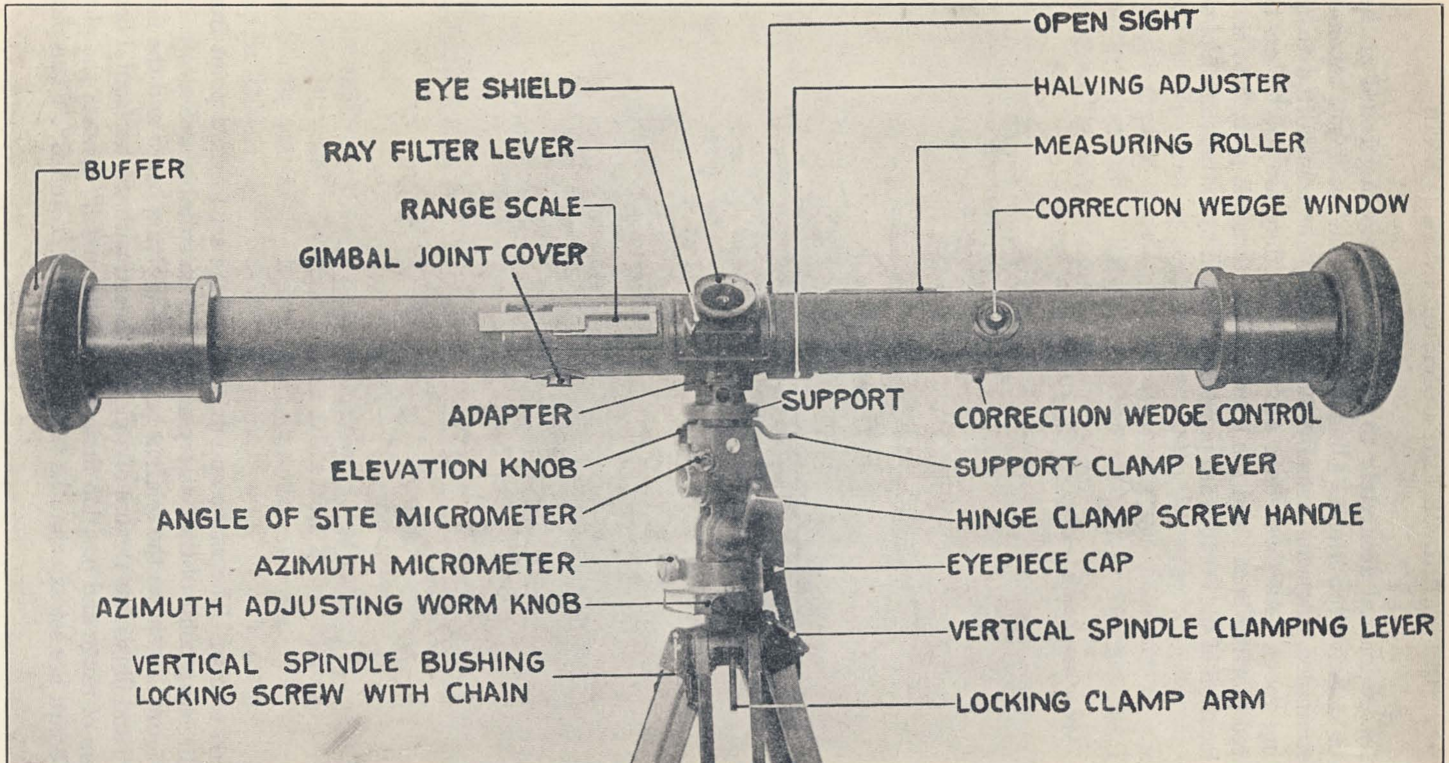


FIG. 285.—Range Finder, Model of 1916 (1-meter Base).

system are located accurately to scale on the plotting board in their correct relative positions. Observation station readings, taken at predetermined intervals (usually 30 seconds), are transmitted to the plotting room. As these data are received, they are set off on the oriented plotting board and the course of the target is plotted to scale. The location of the set forward point is predicted by extrapolation of the

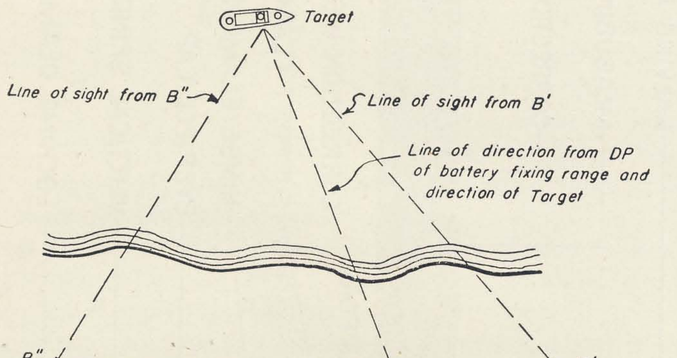


FIG. 286.

plotted course. The range and azimuth of the set forward point from the directing point of the battery are read from suitable scales.

Figure 286 shows the relation between a plotting board and the field of fire and illustrates the use of a plotting board with the horizontal base system of range and position finding. The B' and B'' arms of the plotting board are set at azimuths transmitted from B' and B''. The plot-

ted position of the target is at the intersection of the fiducial edges of these arms. The gun arm is graduated in range, hence the range and azimuth of the target from the directing point are read by placing the fiducial edge of the gun arm over the plotted point.

The more recent plotting boards differ from that shown in Fig. 286 in that the target is considered stationary and the successive relative positions of the directing point with respect to the target are plotted. This permits greater flexibility in shifting from one base line to another, and in relocation of the target. The Plotting and Relocating Board shown in Fig. 287 operates on this principle.

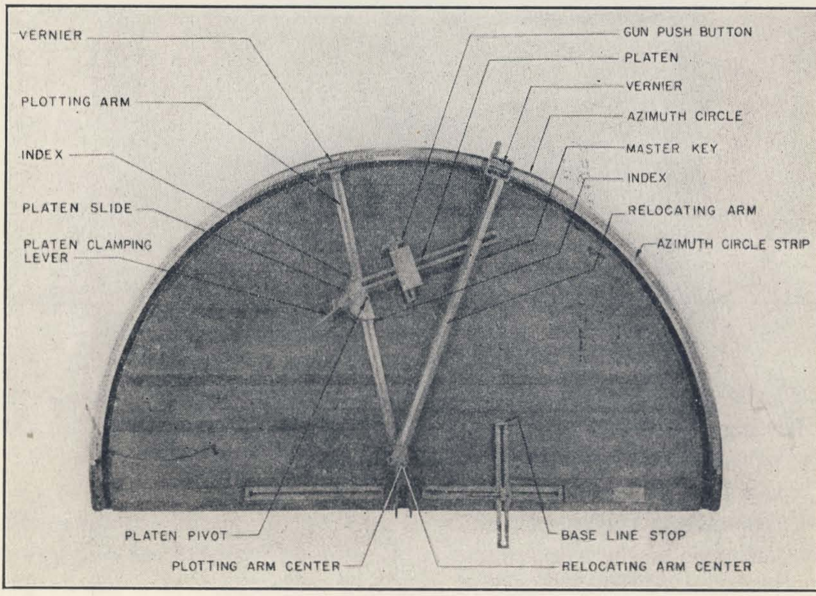


FIG. 287.—Plotting and Relocating Board.

On the board the pivot of the plotting and relocating arms represents the target. The distance between the platen pivot and the vertical edge of the master key represents the base line to scale. The gun push button represents the battery directing point. The base line stop is used for the original orientation of the board and for maintaining the orientation of the base line for each setting of the plotting arm.

Between settings of the plotting and relocating arms, the platen clamp is released and the platen slide brought down against a stop on the pivot end of the plotting arm. The edge of the platen is kept against the base line stop. When the plotting arm is set in azimuth the platen

clamp is tightened; and, when the relocating arm is set, the platen slide is moved up the plotting arm until the master key touches the relocating arm. The position of the directing point is plotted by pressing the gun push button. Ranges and azimuths are read from the relocating arm.

All the scales on this board are replaceable, and the positions of the gun push button and master key are adjustable; thus the board may be adapted for almost any set of conditions.

335. Range Correction Board.—The Range Correction Board, M1, shown in Fig. 288, is used principally by seacoast artillery. Its function

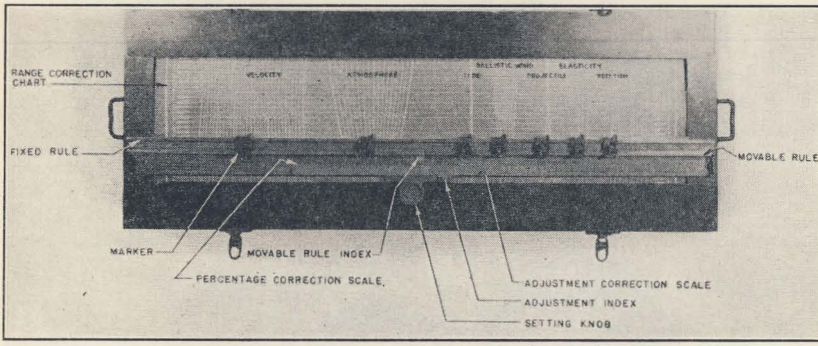


Fig. 288.—Range Correction Board, M1.

is to compute mechanically the amount of range correction due to the following variations:

Variation from standard muzzle velocity.
Variation from normal air density.
Variation of the tide effect.
Variation of the wind effect.
Variation from the standard weight of projectile.
Variation in the temperature elasticity effect.
Variation in the rotation of the earth effect.

The board provides a means of determining the corrections rapidly and combining them to determine the net correction as a percentage of the range. The essential parts of the board are the range correction chart, the movable horizontal rule with markers, and the percentage correction scale, the last named being used in connection with the range percentage corrector to obtain the corrected range.

Separate charts are attached to the rollers for each caliber of gun, each type of projectile, and each muzzle velocity. The charts are graduated in range and contain correction curves for variations of each of the factors mentioned above. Construction of these curves is based

on data contained in the firing tables. The range effects in yards, or percentage of range due to non-standard conditions, are extracted and plotted on both sides of the normal of the horizontal range line. Points are then similarly plotted for various other ranges and the corresponding variation points at the different ranges are joined to form the curves.

The mechanical operation of the board is governed by the range setting and the indicated correction curves. Each marker is designed so that it may be clamped to the movable rule, the fixed rule, or to both. A marker is moved by clamping it to the movable rule and rotating the

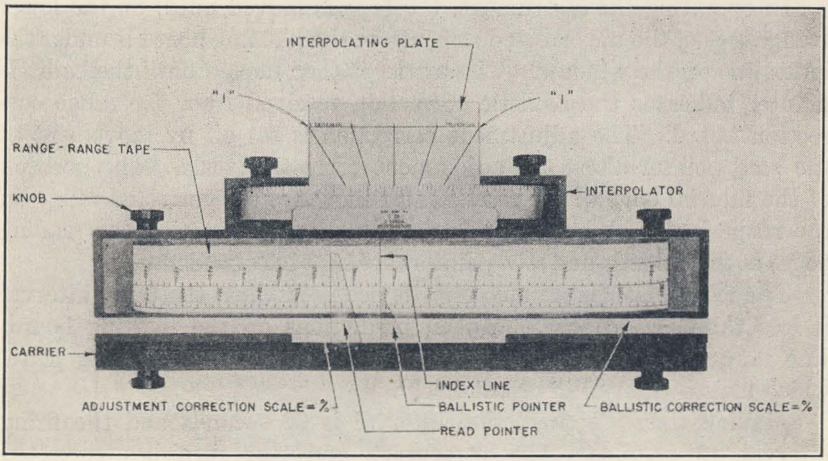


FIG. 289.—Percentage Corrector, M1.

setting knob. When all markers indicate the normal curve and are clamped to the fixed rule, the movable rule index is placed opposite the zero on the percentage correction scale. Each marker in turn is then clamped to the movable rule and set at the proper correction curve. When all corrections have been set off, the net percentage correction is indicated on the percentage correction scale. An adjustment scale and index are provided to permit the introduction of a fixed or battery commander's adjustment correction.

336. Percentage Corrector.—The Percentage Corrector, M1 (Fig. 289), used principally by seacoast artillery, provides a mechanical means of applying ballistic and fire-adjustment corrections to the actual range to obtain the *corrected* range or elevation.

A cloth-backed tape bearing logarithmic range-range, or range-elevation scales is wound on the rollers at each end of the instrument. Range-range scales are used to indicate the range relation where the

charge, projectile, or muzzle velocity in use differs from that for which the range drum on the gun carriage is graduated. Range-elevation scales are used to effect conversions from ranges to elevations.

The graduations on the ballistic correction and adjustment correction scales represent percentages. The ballistic correction scale is fixed, its zero graduation coinciding with the index line on the window. The adjustment correction scale, with the ballistic pointer at its zero graduation, is mounted on a movable slide called the carrier. The *read* pointer is fastened to a sliding block which may be moved along a groove in the carrier.

In operating the instrument, the tape is moved until, on the lower (range) scale, the uncorrected range from the plotting board is under the index line on the window. The carrier is then moved until the ballistic pointer indicates the ballistic correction received from the range correction board. The adjustment correction is set off by movement of the *read* pointer along the adjustment correction scale. The position of the fiducial edge of the *read* pointer indicates the corrected range on the range scale. When there is no adjustment correction the reading edges of the ballistic and *read* pointers are kept in coincidence.

The *interpolator* is an auxiliary device used when the firing interval is less than the interval between predictions on the plotting board. The range tape of the interpolator runs over the interpolating plate, which may be moved in or out freely.

Assume that the prediction interval is 30 seconds and the firing interval 15 seconds. The percentage corrector furnishes corrected ranges at 30-second intervals. The intermediate ranges are obtained by movement of the interpolator range tape and the interpolating plate so that the *central* line "1" and a *diagonal* line "1" indicate, respectively, the last and next to last ranges obtained from the percentage corrector. A diagonal line "3" then indicates the following intermediate range.

337. Deflection Board.—The Deflection Board, M1 (Fig. 290), is used by seacoast artillery for the mechanical computation of corrected azimuths. It consists essentially of a wind component indicator, an azimuth correction and adjustment mechanism, a displacement corrector, and an angular travel device.

The *wind component indicator* graphically determines the intensity of the range and deflection components of the ballistic wind. The azimuth scale of the indicator is geared to the main azimuth circle so that the range component axis on the fixed base plate always represents the target azimuth. The wind bar, which is set at the wind azimuth, also rotates with the azimuth scale. The distance of the wind velocity pointer from the center of the wind bar represents the wind velocity.

The position of the wind velocity pointer on the base plate indicates the range and deflection wind components.

The principle of applying wind, drift, earth rotation, and adjustment corrections is similar to that used on the Range Correction Board, M1. A suitable deflection chart for the gun, projectile, and muzzle velocity used is mounted on rollers. This chart contains range graduations and two sets of azimuth correction curves, one set for wind and drift effects

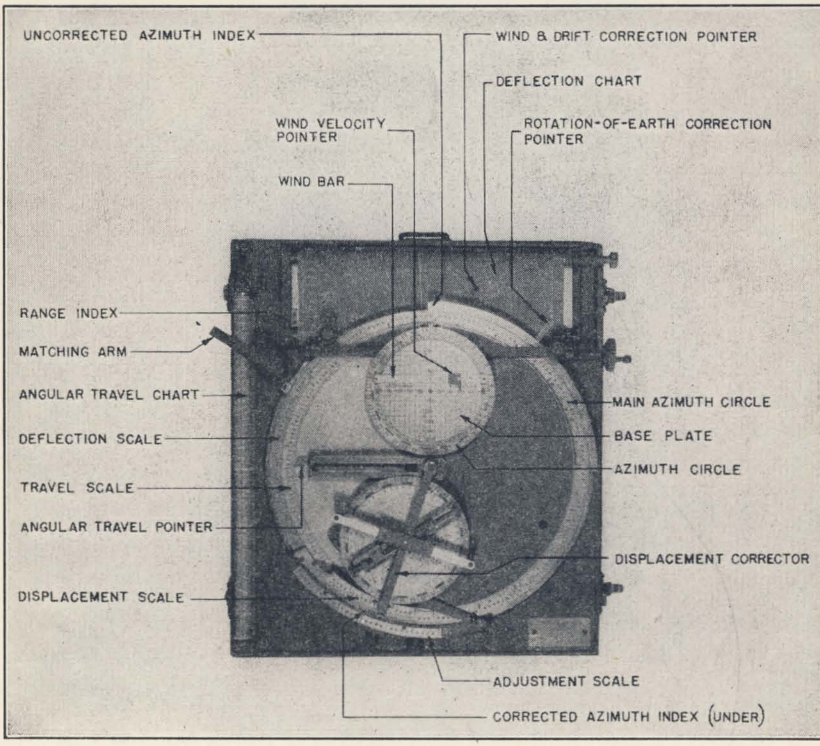


FIG. 290.—Deflection Board, M1.

and another for earth rotation effects. Each set of curves contains a zero deflection line. With the proper range graduation on the chart set opposite the range index, and each of the correction pointers set at the zero deflection line, the main azimuth circle is moved so that the uncorrected azimuth appears opposite the uncorrected azimuth index. Under these conditions, with a zero adjustment correction, the corrected azimuth index also indicates the same azimuth. From this point on, the arrangement is such that movement of either pointer to the proper correction curve changes the relative positions of the main azimuth

circle and the corrected azimuth index. The change in azimuth readings is a measure of the angular travel of the pointer and is the azimuth correction for the effect represented by the correction curve. The corrected azimuth index is integral with the adjustment scale and opposite its zero graduation. Adjustment corrections are set off by shifting this scale with respect to the adjustment index.

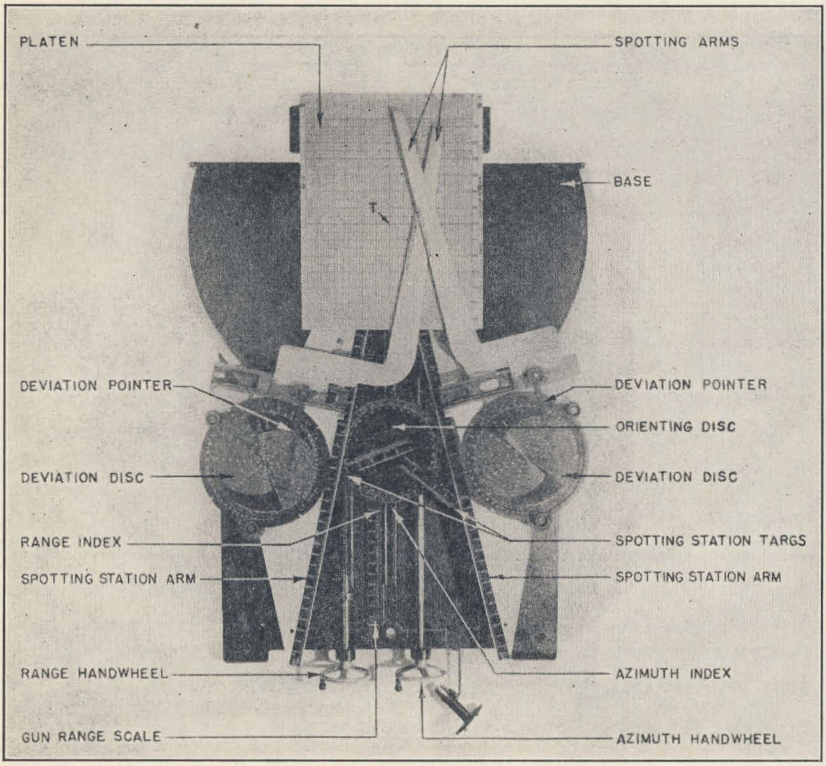


FIG. 291.—Spotting Board, M2.

The *displacement corrector* is used to determine the corrected azimuth for a gun displaced from the directing gun or point.

The *angular travel device* is used to determine the angular travel of the target during the time of flight of the projectile. This device is used when the gun is set in azimuth by means of a sight. The angular travel correction is automatically combined with the other deflection corrections, and the corrected angle thus obtained is set off on the sight.

Spotting Board.—The Spotting Board, M2 (Fig. 291), is used by seacoast artillery, in connection with bilateral spotting systems, to

determine the range and deflection deviations of the point of impact from the target. The deviations obtained from the spotting board are applied as adjustment corrections through the percentage corrector and deflection board.

The center (T) of the platen represents the target. The spotting station arms rotate about a stud directly below T, and are grooved to fit the spotting station targs. These targs represent the spotting stations, and the center of the orienting disc corresponds to the directing point. The arms on the orienting disc are adjusted so that the positions of the targs with respect to the center of the disc represent, to scale, the actual relations of the spotting stations and the directing point.

A *deviation measuring mechanism* is mounted on each spotting station arm. This mechanism consists of a movable spotting arm bearing a deviation pointer, and a deviation disc assembly. The fiducial edges of the spotting arms always remain parallel to the spotting station arms, and correspond to the lines of sight from the spotting stations to the point of impact. The deviation pointer represents the splash pointer of an azimuth instrument, and its trace on the deviation disc corresponds to the deflection scale on the reticle of the same instrument. The deviation disc assemblies permit the use of an exaggerated scale for the area surrounding the target and further provide for the use of fixed deviation scales on the platen.

In orienting the board, the orienting disc assembly is moved by means of the range handwheel until its range index indicates the directing point-target range. The assembly is then rotated by means of the azimuth handwheel until the azimuth of the target, from the directing point, appears opposite the azimuth index.

If the board is properly oriented and the deviation pointers are at the centers of the deviation discs, the fiducial edges of the spotting arms will intersect at T, the center of the platen. With the deviation discs adjusted for range, the pointers are moved to the proper deviation curves. The fiducial edges of the spotting arms then intersect in a point whose coordinates on the platen scales are the desired range and deflection deviations.

When range deviations are read in percentages of the range the deflection deviations are read in degrees and hundredths. Deviations may be read in yards by using scales on the reverse sides of the platen and deviation discs.

CHAPTER XIV

FIRE CONTROL FOR ANTIAIRCRAFT ARTILLERY

338. Antiaircraft Gun Fire.—The advent of the airplane has presented a new problem in fire control. Owing to the small size of the target and its rapid three-dimensional movement in space, a system of automatic computation and transmission of firing data to the gun battery has become necessary. In terrestrial fire, the point of fall of the projectile and, hence, the chord of the trajectory are of primary importance. In antiaircraft fire, the shape of the trajectory itself and the variations in the arc for the entire range of gun elevations must be considered.

Automatic fire control may be applied to targets on land and sea or in the air. The system includes a height or range finder, a data-computing director, a battery of guns, and a self-synchronous data-transmission system. For operation at night, it is necessary to add a sound locator with sound-lag corrector, and a searchlight with control station.

Time is the most essential factor in the application of an automatic and continuous fire-control system. The target must be accurately positioned, the firing data automatically computed, and the necessary shots fired to destroy the target, during the time interval after the target comes within range and before it is in a position to drop its bombs effectively.

Figure 292 shows the time chart for a bomber traveling at 200 miles per hour and at an altitude of 6000 yd. The director begins tracking at R, and firing starts when the target is at S. The projectile meets the target at the predicted point T. The distance ST represents the travel of the target during the time of flight of the projectile from 0 to the point T on the envelope of the gun trajectory. The bomber must be destroyed or forced to turn back prior to its arrival at the point of bomb release. The chart indicates the necessity for echelon in depth of the components of the defense system.

339. The Director.—The computing director is the heart of the antiaircraft defense system. It receives continuously the present azimuth, the present elevation, and the height of the target. These data are automatically digested to produce the angle of traverse, the quadrant elevation, and the fuze setting, for transmission to the guns.

It operates on the assumption that, during the time of flight, the most probable course for opposing aircraft, particularly massed formation flights, will be a continuation of a linear course at a constant speed. Prior to bomb release the airplane must be aligned in a definite direction, which necessitates flying on a linear course for a limited period of time. Necessary corrections for variations from constant height can be made by means of spotting controls on the directors.

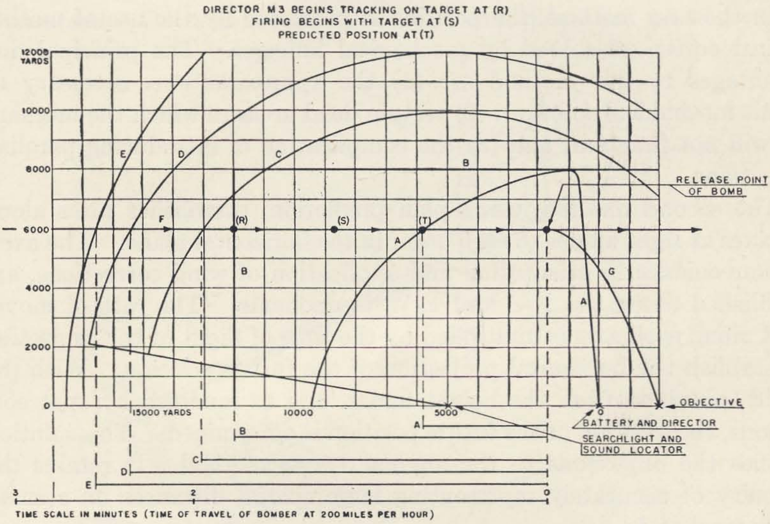


FIG. 292—Time Limitation in Antiaircraft Fire.

A. Envelope, 3-in. Antiaircraft gun.
B. Prediction limits.
C. Range illumination, searchlight.
D. Effective sound locator range.
E. Limit of visibility.
F. Path of bomber at 6000 yd. altitude.
G. Bomb trajectory.

The director is intended to perform three essential functions, namely:

(1) Determination of the present position of the target.
(2) Prediction of future position, for travel of target during time of flight of projectile.
(3) Computation of ballistic data, so that burst will occur at predicted position of target.

The present position of the target is determined by tracking telescopes, one for elevation and one for azimuth, and a height finder which measures continuously the vertical height of the target. The height

of target is transmitted electrically to the director, where it is combined with present elevation and azimuth to fix the location of the target in space. The tracking telescopes are located on the director. The height finder is a separate instrument.

The future position of the target is obtained by multiplying the rate of movement of the target by the computed time of flight of the projectile. The solution may be by the angular travel method, using angular rates, or the plan prediction method, using linear rates.

In the first method, the position is predicted by the use of mathematical equations solved by mechanical linkages. The principal disadvantages to this method are (1) the approximations necessary to permit mechanical solution; (2) certain dead areas in which the mechanism will not function; and (3) the complication of introducing parallax corrections.

The second method, using plan prediction, establishes rates along two axes at right angles to each other in the horizontal plane. The axes, for convenience in orientation and application of wind corrections, are established along the N-S and E-W components. The rate of movement along each axis is multiplied by the time of flight of the projectile, to establish the horizontal projection of the future position. With the height, obtained from the height finder, and as modified by spot corrections, the location of the future position is determined. This solution satisfies the objections to the angular travel method. It retains the difficulty of accurately representing large spatial distances on a small mechanical scale.

The computation of ballistic data involves adding the normal superelevation to the line of site from the gun to the future position, to obtain the quadrant elevation. The normal quadrant elevation must then be corrected for the following changes: (1) variation in muzzle velocity, (2) variation in air density, and (3) direction and velocity of ballistic wind. The future azimuth must be corrected for the cross wind and the drift of the projectile. The fuze setting is based on the corrected quadrant elevation.

The two principal methods of computing ballistic data are the three-dimensional cam and the use of charts on cylinders which revolve under movable pointers.

The three-dimensional cam is simply a range table represented in physical dimensions. Each plane section through an axis represents a specific firing table condition. The quadrant elevation cam (Fig. 293) includes the angular values of the future angular height and the normal superelevation. In operation the cam is rotated in terms of R_p, the future horizontal range. The follower pin is translated along the surface

of the cam in terms of H_p, the future altitude. The follower obtains the output of the cam as the radial distance out from the cam axis in terms of Q. E., quadrant elevation. The method of applying corrections for off-normal conditions is described later under ballistic mechanism.

Charts, as used in certain directors, are height curves on cylindrical drums which rotate in future angular height with normal superelevation as ordinates. By matching the proper height curve with a pointer moving along a vertical screw, the ordinate or superelevation can be determined. Corrections for off-normal conditions are made by sub-

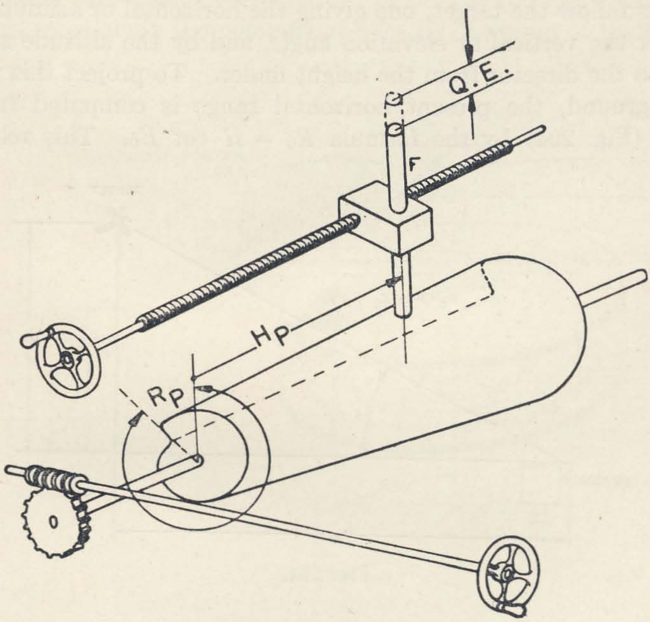


FIG. 293.—Three-dimensional Cam.

stitution of the normal chart on the cylindrical drum by another, having displaced height curves to suit the particular conditions. A nest of charts is furnished with each director of this type to provide for the spread of off-normal conditions usually experienced.

Types of Directors.—The directors approved as standard for issue to the U. S. Army comprise the M1, M2, M3, and M4 models. Except for the M1, all these models use the plan prediction method to predict the future position of the target and compute the ballistic data by three-dimensional cams. They are designated as universal directors against aircraft, land, and water targets; and they include a volume with 360° traverse, 10° depression, and 90° elevation. The plan prediction

directors may be subdivided into the following essential component mechanisms:

a. Present position mechanism.
b. Prediction mechanism.
c. Ballistic mechanism.
d. Spotting controls.

Present Position Mechanism.—The position of the target in space at any time is determined by means of two telescopes with which the operators follow the target, one giving the horizontal or azimuth angle, the other the vertical or elevation angle, and by the altitude as transmitted to the director from the height finder. To project this position on the ground, the present horizontal range is computed from the triangle (Fig. 294) by the formula $R_0 = H \cot E_0$. This relation is

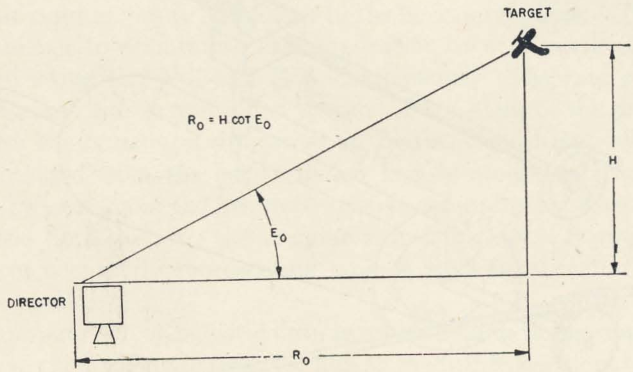


FIG. 294.

solved mechanically within the director by a three-dimensional cam, which rotates with altitude and translates with horizontal range, the lift of the pin resting on the cam representing angular height. When altitude is set and the angular height obtained from the cam lift matches the angular height from the elevation tracking telescope, the correct horizontal range is determined. The present horizontal range, as determined and set in the director, moves a pin to the corresponding distance from a fixed center, whereas the angular positioning of the pin is done by the azimuth tracking telescope.

The mechanism which locates the horizontal projection of the target, and continuously establishes its displacement from the E-W and N-S reference axes through the origin, is shown schematically in Fig. 295. Rotation of the upper disc locates the movable pin according to present

azimuth A_0. Rotation of the lower disc, containing the equiangular spiral groove, moves the pin along the radial groove of the upper disc according to present horizontal range R_0. As the pin is thus positioned in range and azimuth, it in turn positions the pair of slides and establishes the displacements, X_0 and Y_0, of the target from the E-W and N-S lines through the origin. As the target is tracked, the mechanism automatically and continuously locates it with reference to these axes. The next step requires the measurement of the rate of movement with respect to these axes.

Prediction Mechanism.—Prediction consists of the multiplication of the target rates along the component axes by the time of flight of the

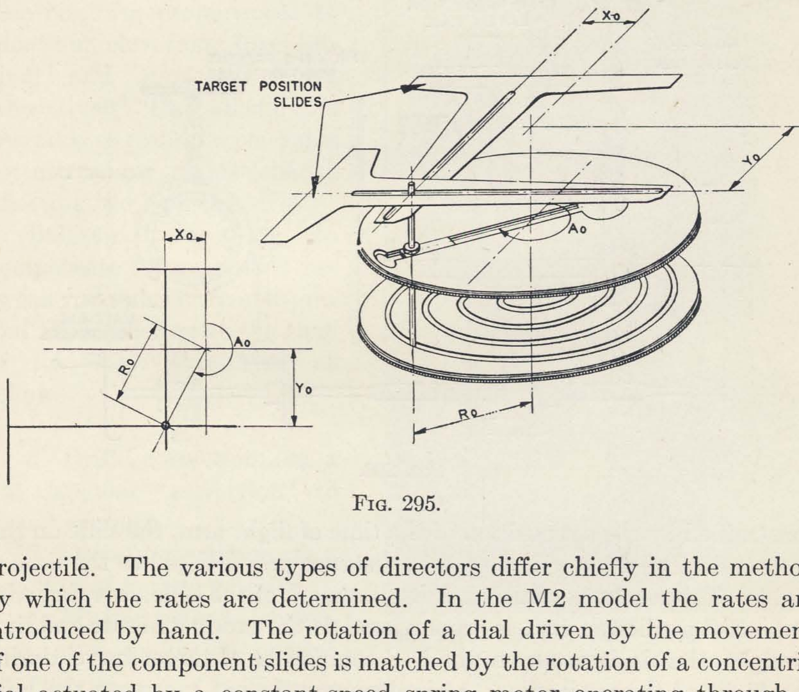


FIG. 295.

projectile. The various types of directors differ chiefly in the method by which the rates are determined. In the M2 model the rates are introduced by hand. The rotation of a dial driven by the movement of one of the component slides is matched by the rotation of a concentric dial actuated by a constant-speed spring motor operating through a variable-speed drive. The setting of the variable-speed drive to obtain a match between the concentric dials is a measure of the rate. The rate is then multiplied in a linkage by the time of flight to obtain the prediction. The disadvantages of the spring motor led to development of the tachometer method of rate measurement employed in the M3 model. In this model the movements of the component slides are geared to the stems of tachometers which are in effect reversible-reading stop watches. The tachometers are actuated by a trip lever which

causes them to measure accurately the target rate for exactly 3 seconds, which is sufficient to smooth out any irregularities caused by the tracking operators. The dials of the tachometers are graduated in terms of target rates (yards per second) along the respective component axes. The measured rates are then matched by a setting handwheel which also introduces the proper rate to the multiplying linkage in order to obtain the desired prediction. The N-S prediction mechanism is shown schematically in Fig. 296. The operator has only to match pointers in the tachometer by use of the handwheel. This displaces the pivoted lever a horizontal distance proportional to the N-S travel rate. Also, as

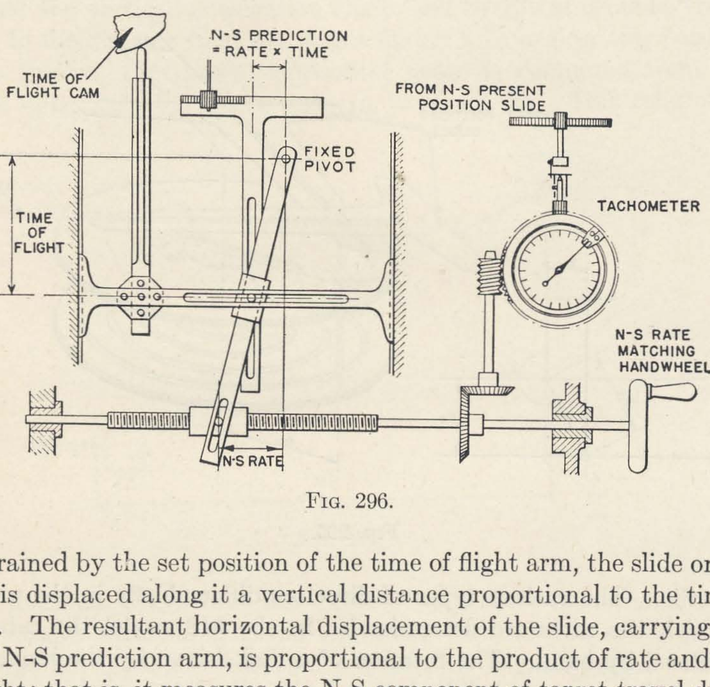


FIG. 296.

constrained by the set position of the time of flight arm, the slide on this lever is displaced along it a vertical distance proportional to the time of flight. The resultant horizontal displacement of the slide, carrying with it the N-S prediction arm, is proportional to the product of rate and time of flight; that is, it measures the N-S component of target travel during the flight of the projectile. A similar arrangement measures the E-W travel component.

The travel components are mechanically combined with present position components to establish the future position components. An adjustment for the N-S and E-W components of the battery offset (parallax correction) is introduced between the present position slides and the future position slides, permitting displacement of the director to a location a considerable distance from the battery.

The N-S and E-W components of future position are converted to

future horizontal range and future azimuth by a system of discs and slides similar to those employed in determining components of present position. This is accomplished continuously and automatically by an electromechanical follow-up system.

Ballistic Mechanism.—The third essential function of a director is the computation of the firing data based on the future position of the target. This involves primarily the determination of the quadrant elevation, the fuze setting, and the time of flight, which is used in determination of prediction. Each of these elements of ballistic data is incorporated in a three-dimensional cam. The cams translate in altitude, H_p, rotate in range R_p, and have cam-pin lifts proportional to quadrant elevation, fuze setting, and time of flight, respectively. The ballistic cam assembly is readily replaceable to meet any major change affecting the ballistics.

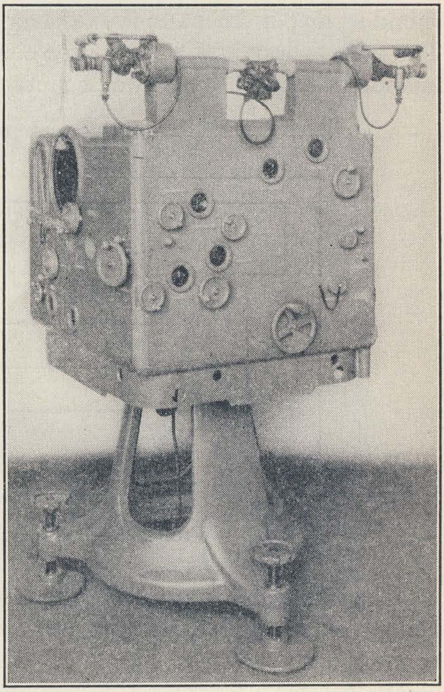


FIG. 297.—Director M3. Rear View with Spot Controls.

Ballistic corrections, to compensate for variations between standard conditions and those existing at the time of fire, are introduced as follows:

a. Drift correction, as a flat angular correction to future azimuth.

b. Density correction, as a function of muzzle velocity.

c. Muzzle velocity correction, as a change in present altitude.

d. Wind corrections, as corrections to target rates.

Spot Corrections.—Despite all precautions, errors may arise due to erroneous meteorological data, target maneuvers, inaccurate height measurement, or other cause. Frequently, corrections to firing data are indicated as the results of trial shots or calibration firing. This necessitates a provision in the director for control of fire by means of spot corrections for observed deviations. The spotting controls are

grouped on the rear face of the director below the spotting telescope. The spotting handwheels are equipped with spring detents so that the corrections may be inserted by feel without removing the eye from the spotting telescope.

340. Data Transmission.—The two basic systems of data transmission are the D. C. step-by-step system and the A. C. self-synchronous system. The A. C. self-synchronous system has been adopted as standard for the U. S. Army.

A self-synchronous system is defined as one in which a displacement of the transmitter motor is compensated for automatically by a corresponding displacement on the receiver motor when the current is applied. The system provides a means for continuous and instantaneous transmission of data between two or more remote units.

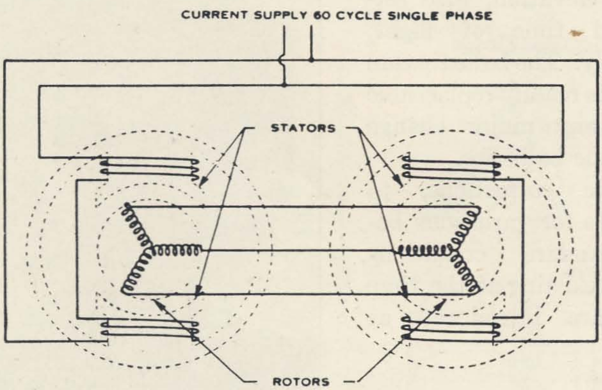


FIG. 298.—Self-synchronous Motors.

The transmitting and receiving motors are identical electrically, both being small bipolar three-phase alternators. The two motors are connected as shown in Fig. 298. The two stators are excited from a common 110-V., 60-cycle, single-phase A. C. source. Assuming that the rotors are free to turn, they will take such a position that the voltages induced are of balanced magnitude and displacement. Any motion given to the rotor of one unit will be transmitted to and duplicated by the rotor of the other unit.

In multiple operation, for example, when one azimuth or elevation transmitter in the director operates 4 receivers at the guns, the transmitter must be made larger and of such characteristics that each receiver will develop its standard torque.

Each transmitter is capable of controlling its receiver motor to a precision of $\frac{1}{2}°$. If more accuracy is desired, the data are broken up

into two parts, coarse and fine, transmitted and received by separate motors. Both elevation and azimuth data are thus transmitted, the addition of the fine or vernier motors giving accuracy to $\frac{1}{32}°$ or 0.55+mil.

A complete data-transmission system includes the necessary cable,

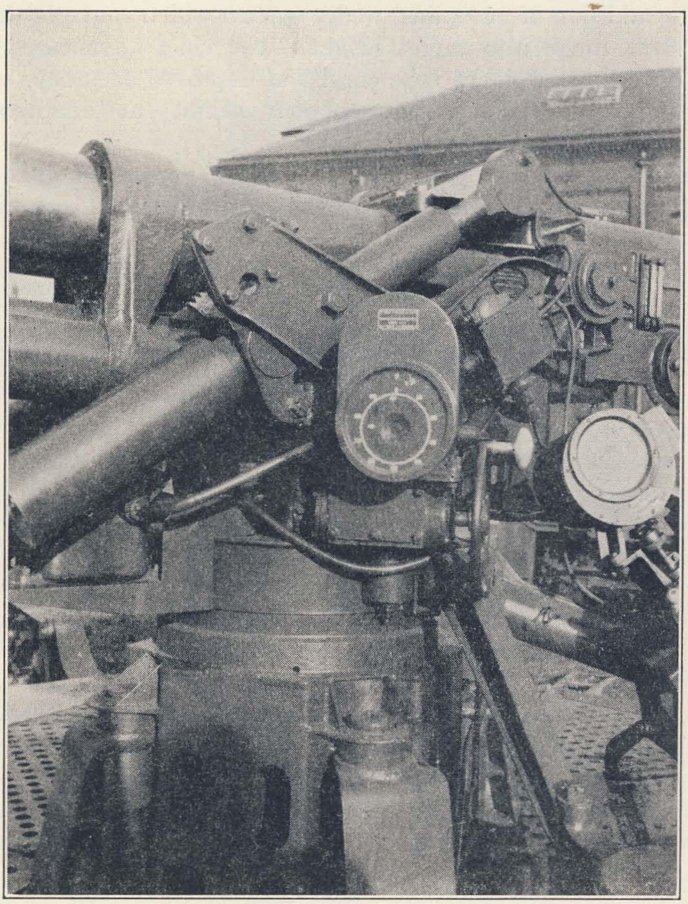


FIG. 299.—Azimuth and Fuze Indicators, 3-in. A. A. Gun Mount, M2.

a main junction box, 4 gun distribution boxes, and an elevation, azimuth, and fuze receiver for each gun.

341. Height Finder.—The vertical height of the target is measured separately and transmitted continuously and automatically to the director. This height is determined by a self-contained height finder of the stereoscopic type, or by the two-station method using instruments

at the end of a measured base line. Theoretically, the latter method is the more accurate, but it is complicated by the necessity for accurate orientation, maintenance of communications, and means for mutual target identification.

A stereoscopic height finder (Fig. 300) is primarily a range finder with the addition of an optical wedge system which converts the measured slant range into target height. The chief advantages of the stereo over the coincident type consist of improved accuracy, superior ability to function under conditions of poor visibility, and adaptability to operate on small, fast-moving targets.

Stereoscopic vision is the power of depth perception, due to the spacing or interpupillary distance of the eyes, which results in different

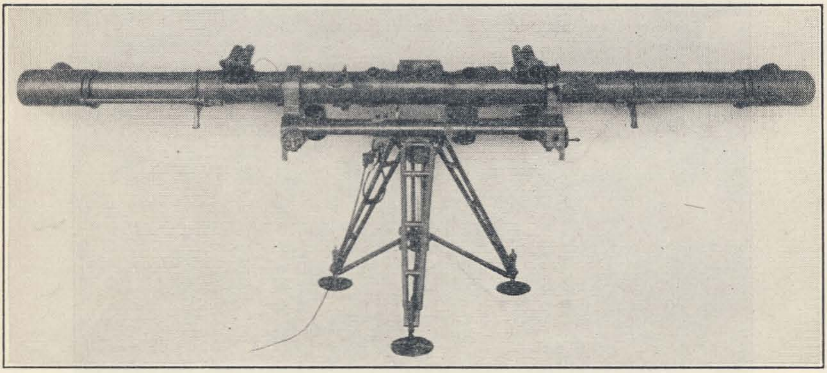


FIG. 300.—Height Finder, M1, Rear View.

images being formed on the retinas of the eyes. In a range finder, the power of depth perception is increased owing to the magnification employed and the base length of the instrument, which becomes the effective spacing of the eyes. A system of reticle marks and optical wedges is included in the range finder to permit accurate measurement of the slant range, i.e., location of the target in depth.

The function of the reticle marks may be illustrated graphically (Fig. 301). When the reticles are directly in front of the eyes the incoming rays are parallel and the reticle appears at infinity, as is the sense when gazing at a star. Assuming the right reticle capable of movement along the axis to the respective positions, 1, 2, and 3, the two images in the eyes will combine to sense the position of the reticle in space at the distances I, II, and III. The movement of the reticle along the axis from 1 to 3 is a measure of the distance in space from I to III. If the reticle be moved so that the central mark appears to be at the same

distance in space, as an airplane at II, the movement of the reticle can be used as a measurement of the range of the airplane.

In practice, for greater accuracy, the same objective is obtained by holding the reticles in fixed positions and moving the right image of the

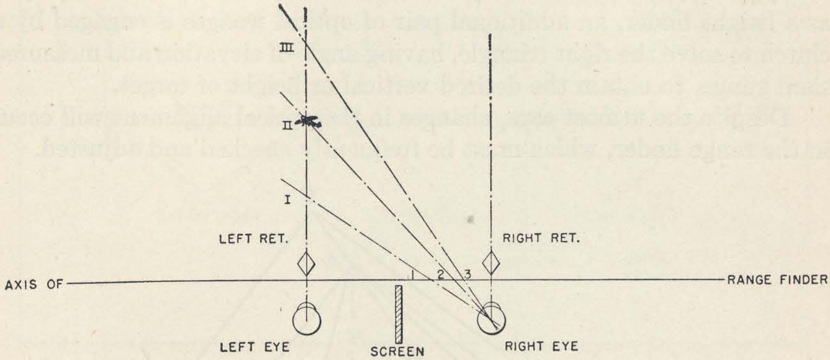


FIG. 301.

target (Fig. 302). The effect on the observer is the same, in that the target appears stationary while the reticle appears to move upon change of range. An optical ray from an infinite source will be deflected 90° by the end reflectors and travel along the axis of the range finder until it strikes the optical wedge W_α, where it will be deflected to the point M

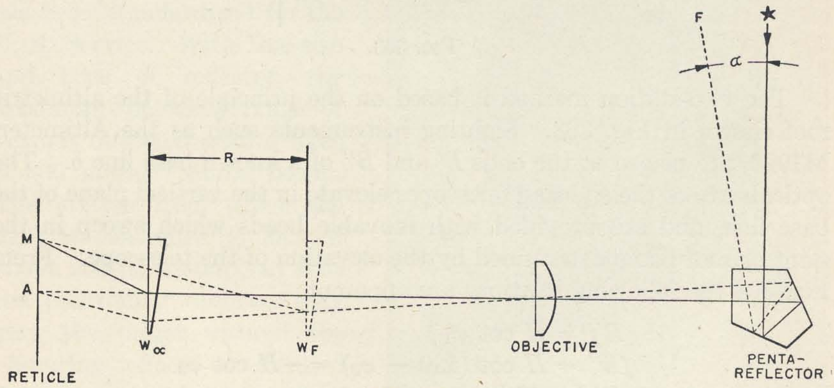


FIG. 302.

on the reticle. The point M is the location of the reticle mark. An optical ray from a finite target F entering the range finder at the angle α is deflected at W_α to strike the reticle at some point A. To make A and M coincide it is necessary to move the optical wedge a distance R

to a new position W_F. The distance R which it was necessary to move the optical wedge represents the range of the target. Actually, a pair of wedges is rotated, instead of translating a single wedge to produce the same effect, and the motion is transmitted by gearing to a visible scale where range is read directly. When the instrument is employed as a height finder, an additional pair of optical wedges is engaged by a clutch to solve the right triangle, having angle of elevation and measured slant range, to obtain the desired vertical or height of target.

Despite the utmost care, changes in the optical alignment will occur in the range finder, which must be frequently checked and adjusted.

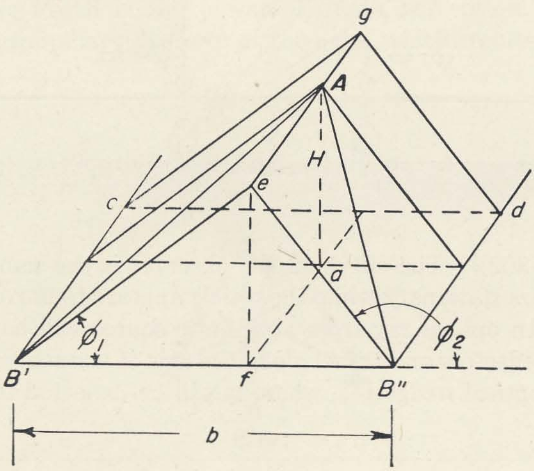


FIG. 303.

The two-station method is based on the principle of the altimetric roof shown in Fig. 303. Sighting instruments such as the Altimeter, M1920, are placed at the ends B' and B'' of a known base line b. The optical axes of the sighting telescopes elevate in the vertical plane of the base line, and are provided with movable heads which sweep in the slant or roof plane determined by the elevation of the telescope. From Fig. 303 the following relations are apparent:

$$B'f = H \cot \varphi_1$$
$$fB'' = H \cot (180 - \varphi_2) = -H \cot \varphi_2$$
$$B'f + fB'' = b = H (\cot \varphi_1 - \cot \varphi_2)$$
$$H = \frac{b}{\cot \varphi_1 - \cot \varphi_2}$$

As b is a known measured distance, and φ_1 and φ_2 are measured by the altimeters, it is possible to determine H.

342. Night Operation.—To illuminate targets operating under cover of darkness, it is necessary to provide searchlights, control stations for the

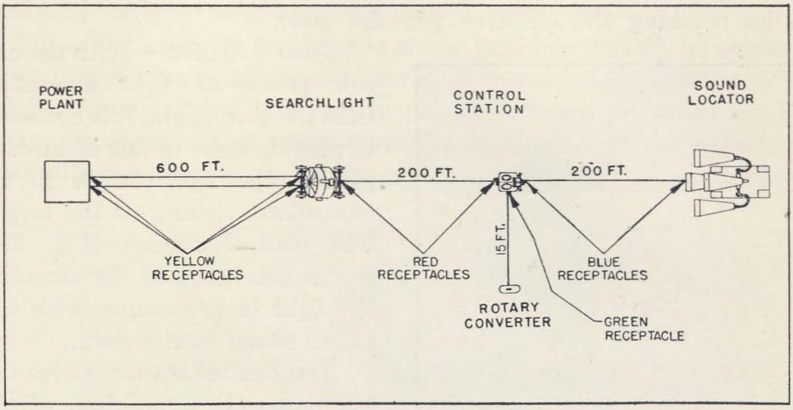


FIG. 304.

searchlights, and sound locators to provide information as to the position of the target. These three units are interconnected electrically, as shown in Fig. 304.

Searchlights.—The 60-in. barrel type searchlight (Fig. 305) with high intensity arc has been standardized for the U. S. Service. With this size and type of reflector, the maximum practical range of beam is obtained with a light of 800 million candle power. The station from which the light is controlled is located about 200 ft. distant, so that the controlling observer may view the target without the obscuring effect of diffused light throughout the length of the beam. A target flying at high altitude will present three or more times greater visible, and hence reflective, surface than a similar airplane at the same slant range but moving toward the light and presenting only the edges of the wings and the front of the fuselage.

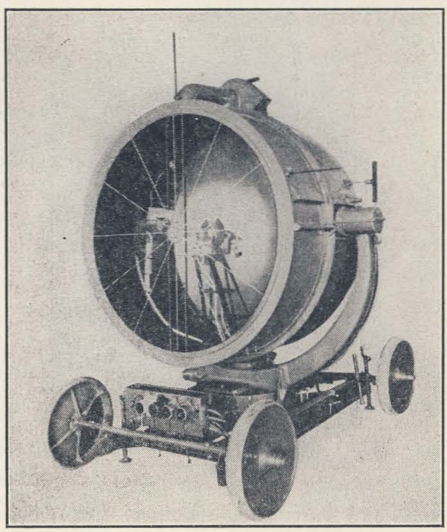


FIG. 305.—60-in. High Intensity Searchlight.

To obtain this more favorable condition of target illumination, the searchlights are advanced far enough in front of the gun battery so that the target may be illuminated at a visual angle of about 40° just prior to its reaching the effective gun fire zone.

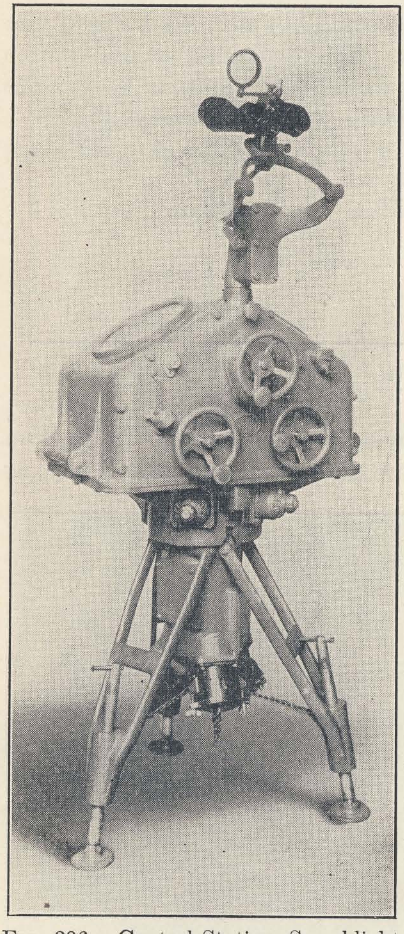


FIG. 306.—Control Station, Searchlight and Sound Locator.

Control Station.—With the narrow pencil of light emanating from the searchlight, it is necessary to provide some means of initially placing the light on or in the immediate vicinity of the target. The control station (Fig. 306) serves this purpose by directing the light in accordance with corrected sound locator data.

The control station serves two functions: (1) comparison of corrected sound-locator data and searchlight position, and (2) actual control of searchlight position by remote electrical control. As a comparator it is provided with two pairs of concentric dials, one representing azimuth and the other elevation. In each pair, the inner dial indicates corrected sound-locator data received by self-synchronous transmission from the acoustic corrector. The outer dial indicates the position of the searchlight. When the concentric dials are matched, the searchlight is positioned according to the corrected sound-locator data.

As a controller the instrument directs the positioning of the searchlight until both concentric dials are matched. This is accomplished by the control station operator, using handwheels connected with two D. C. brush-shifting, step-by-step, transmitter motors. These motors actuate receiving motors at the searchlight which have sufficient torque to move the light in elevation and azimuth.

Sound Locator.—The sound locator (Fig. 307) is used to determine the

direction of aircraft approaching under cover of darkness, fog, or smoke. The data obtained with this instrument are corrected automatically for sound lag by the acoustic corrector, and transmitted to the control station as corrected azimuth and elevation.

The sound locator is constructed on the principle that, if the operator is not directly facing the sound source, the sound wave will reach his two ears with a slight difference in phase, striking one ear an instant before the other. This phase effect is magnified, and the operator's binaural sense sharpened, by the use of horns. The horns, in effect,

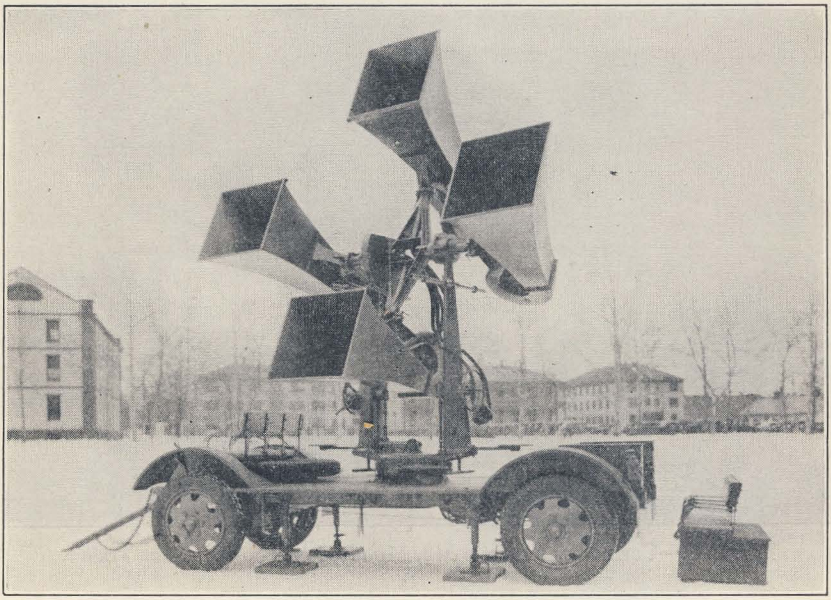


FIG. 307.—Locator, Sound, M1A8, Operating Position.

increase the baseline between the ears to the distance between the horns and, in addition, serve as sound collectors and acoustic amplifiers. Two pairs of horns are provided, one pair for azimuth location and the other for elevation. Each pair is connected with a handwheel, by means of which it is moved until so directed that the sound wave reaches the operator's ears exactly in phase.

Acoustic Corrector.—To determine the position of a moving sound source, such as an airplane, a sound-lag corrector is required. Sound travels at the rate of approximately 1100 ft. per second in still air under normal conditions. Hence, if the slant range of an airplane is 11,000 ft., the airplane will have proceeded 10 seconds on its course when

the sound is received at the locator. Substantial corrections must be applied to the observed azimuth and elevation angles of the airplane in order to determine the present position.

The acoustic corrector (Fig. 308) is mounted on the sound-locator trailer and computes the angular corrections due to sound lag and atmospheric conditions. The altitude or slant range of the target is set in the mechanism as an approximation, and converted into sound seconds of slant range. The sound locator supplies the angular move-

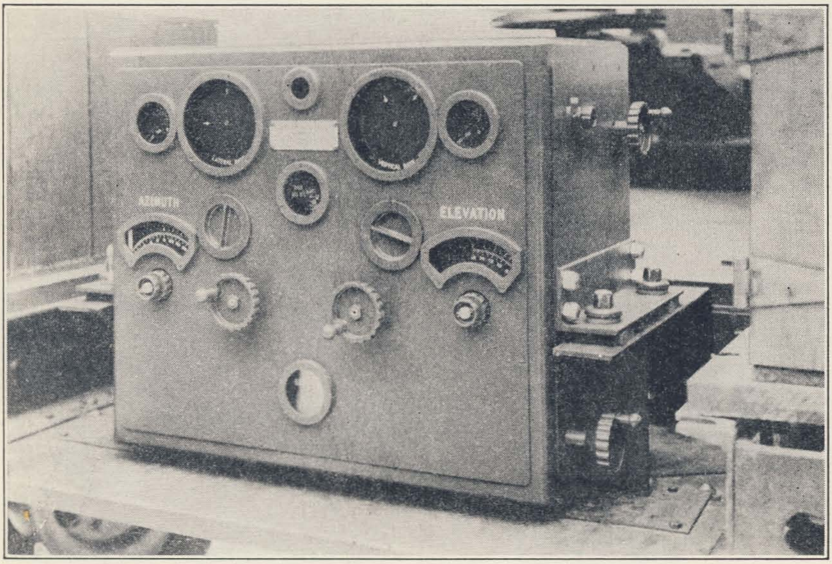


Fig. 308.—Corrector, Acoustic M2, Mounted on Sound-locator Trailer.

ment in azimuth and elevation of the target position. Each angular movement is measured during a fixed period to obtain the respective target rates. Multiplication of the target angular rates by the seconds of sound lag determines the required azimuth and elevation corrections. The corrections combined with the corrections for wind and other atmospheric conditions are added to the sound-locator observations to obtain the corrected or present position of the target. The corrected data are transmitted by self-synchronous motors continuously to the control station and employed in placing the searchlight beam upon the target.

CHAPTER XV

ARTILLERY AMMUNITION

343. General.—The term *ammunition* includes the complete round and all the components or elements thereof. The basic grouping is: *artillery* ammunition for all cannon 20 mm. or more in caliber except trench mortars, *small arms* ammunition for weapons less than 20 mm. in caliber, *trench-mortar* ammunition, *grenades, pyrotechnics,* and *bombs.* Figure 309 shows a complete round of artillery ammunition.

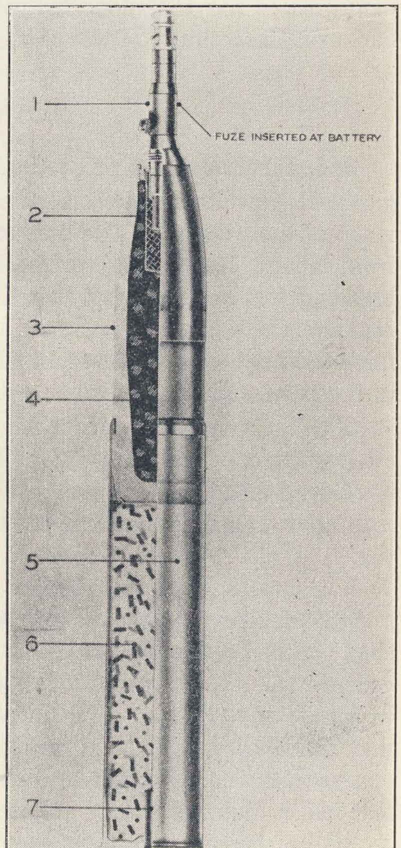


FIG. 309.—Assembled Round, 75-mm. Ammunition.

1. Fuze, point detonating, Mk. III.
2. Adapter and booster, Mk. III-B.
3. High-explosive shell, Mk. IV.
4. Bursting charge, TNT.
5. Cartridge case.
6. Propelling charge.
7. 49-grain primer, Mk. I.

Artillery ammunition is classified according to use as *service, target, drill,* and *blank* or *saluting.* The type classification based upon the design of the projectile for specific tactical use includes *shell, shrapnel,* and *canister.* Shell are designated as *low explosive, high explosive, armor-piercing,* and *chemical,* according to the filler employed and characteristic action. The complete round is designated as *fixed, semi-fixed,* or *separate loading,* according to the manner in which assembled for firing.

The development of effective means whereby definite destructive effects could be produced at exact distant points has been the object of intensive study and research for centuries. The results have exerted a profound influence on the world's

history. The development of the materials of war has been closely associated with the development of strategy and tactics, the changes in one either influencing or being brought about by changes in the other. Likewise, developments in manufacturing processes, technique, tools, and materials have been directly reflected by improvements in the matériel of war; military adaptation has followed closely on technical and industrial advances and, in many instances, military developments and demands have influenced these advances. In no field of ordnance has the modern evolution of matériel exerted a greater effect on the conduct of war than in ammunition.

PROJECTILES

344. Historical.—A projectile is a missile designed to be fired from a gun. Its development has been connected intimately with the development of the weapon. The first recorded use of cannon in warfare dates from about 1350. The projectiles generally were stone balls and, although iron and lead shot came into use at the beginning of the fifteenth century, the stone projectile did not pass completely out of the picture until the beginning of the nineteenth century. Some of those employed in the bronze guns of the time were very large, up to 25 in. in diameter.

The early iron projectiles were solid spherical shot. Bar shot and chain shot, consisting of two iron balls connected by a bar or chain, were developed and used for cutting the masts and rigging of vessels. Chilled iron shot was employed when the first wrought-iron armor came into use.

The hollow spherical shot or shell, filled with a bursting charge of gun powder or with incendiary material, was developed from the solid shot. Another kind of projectile which came into use in the eighteenth century was the case shot, consisting of a number of smaller projectiles in a case or envelope. The three principal types were grape, canister, and spherical case or shrapnel. The first two contained no explosive charge and were designed to break up in the gun or at the muzzle; the last had a bursting charge and a fuze.

Use of spherical projectiles continued until the period of our Civil War when the elongated form, cylindrical with pointed nose, was adopted for use in cannon as it had been previously for hand arms. For a given caliber of weapon, this change of form enabled the use of much heavier projectiles, of increased capacity, and resulted in the attainment of increased range and accuracy of fire. It necessitated, however, provision of means for imparting the necessary rotation to secure stability in flight. In the muzzle-loading cannon of the period,

firing cast iron projectiles, special devices for producing rotation were developed.

The bore of the Whitworth gun, invented in 1857, was a twisted prism of hexagonal cross section. (Fig. 310.) The projectile was fashioned with plane surfaces to correspond. For use in rifled cannon, various means were adopted to attain rotation as illustrated in Fig. 311.

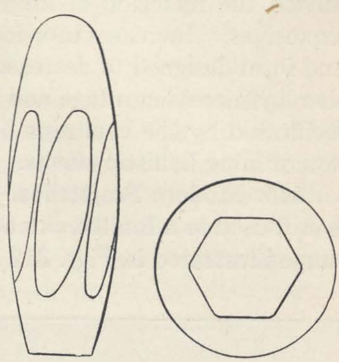


FIG. 310.

In the studded type, protruding studs were fitted into the helical grooves of the rifling as the projectile was inserted in the muzzle. In the Eureka and Butler projectiles the parts a were of soft brass and, in firing, were expanded outward into the rifling by the pressure of the powder gases. Other projectiles were constructed with lead bases so formed that they were forced outward into the rifling. Projectiles of these types permitted considerable escape of powder gas past them, with resulting decrease in velocity and accuracy.

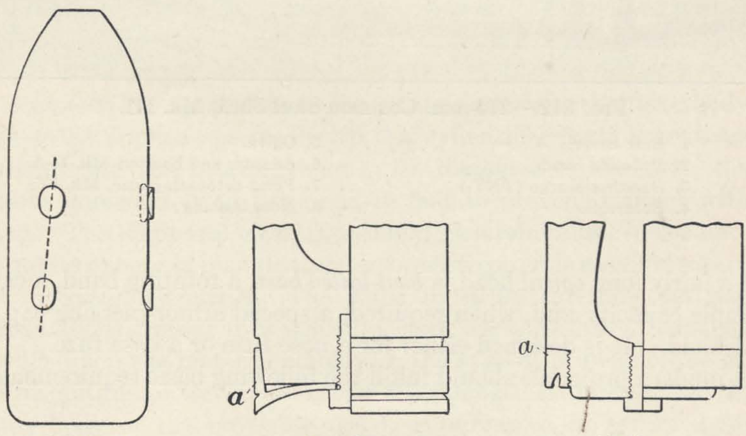


FIG. 311.

The introduction of rifling in cannon was followed shortly by the development of effective methods of breech closure, permitting employment of breech loading. The use of progressive burning propellants and the adoption of smokeless powders of definite chemical composition permitted the attainment of higher velocities with lower pressures.

Developments in metallurgy and in gun manufacture resulted in weapons of greater strength and power. These factors greatly influenced projectile development. The use of steel gave added strength and permitted the inclusion of larger bursting charges of powerful new high explosives. Increases in velocity brought about improvements in shape and form designed to decrease retardation in flight due to air resistance, thereby increasing range and accuracy. Ammunition development was facilitated by the evolution of new and improved means of testing and determining ballistic effects.

345. Modern Projectiles.—With the exception of the canister, which is still used to a limited extent, the modern projectiles are of the general shape illustrated in Figs. 312 and 313. The body is cylindrical in form,

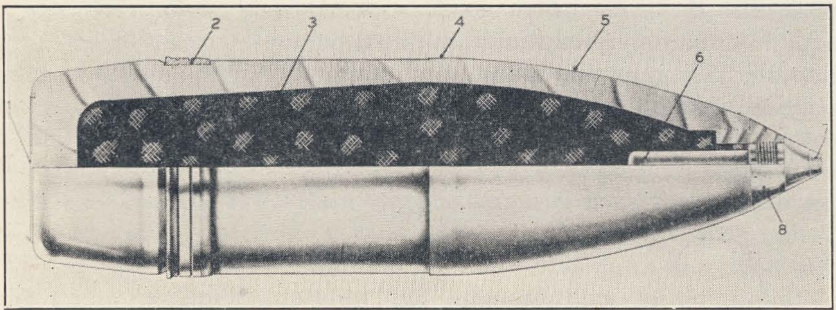


FIG. 312.—240-mm. Common Steel Shell, Mk. III.

1. Base cover.
2. Rotating band.
3. Bursting charge (TNT.)
4. Bourrelet.
5. Ogive.
6. Adapter and booster, Mk. II-A.
7. Point detonating fuze, Mk. IV.
8. Nose bushing.

with a fairly long *ogival* head, a *boat-tailed base,* a rotating band, a cavity of ample capacity and, when required, a special armor-piercing cap and windshield. It is designed either for a nose fuze or a base fuze.

A modern projectile should fulfill the following basic requirements:

Ballistic efficiency, insuring
- Maximum range
- Stability in flight
- Minimum dispersion.

Tactical effectiveness, producing
- Effective fragmentation, or
- Maximum explosive effect, or
- Required armor-piercing capacity, or
- Specific effects specified for special types.

Safety in firing; no prematures due to
- Pressure or shock of discharge in gun.
- Hot gases entering base.

Facility in manufacture, including
- Forging and machining.
- Loading.

346. Characteristics of Projectiles.—*Ogive or Head.*—The head of a projectile is that portion in front of the bourrelet. The curve of the ogive is usually the arc of a circle whose center is on a line perpendicular to the axis and whose radius is expressed in calibers. The radius has been increased in modern projectiles to between 7 and 9 calibers, with marked reduction in air resistance and increase in range. For effective armor penetration a blunter head is required; projectiles designed for such use have a head proper of from $1\frac{1}{2}$ to 2 calibers radius, with a long false head or windshield fitted over it.

Bourrelet.—The bourrelet of a projectile is the cylindrical surface approximately $\frac{1}{6}$ caliber in width in rear of the head. It is accurately machined or ground to give a diametrical clearance between it and the lands of the rifling (in a new gun) varying from 0.005 in. for small calibers to 0.02 in. for a 16-in. gun. Extreme accuracy is essential since the functions of the bourrelet are to center the forward part of the projectile in the bore and to provide a bearing or guide for its travel through the bore.

Body.—While applicable to the entire projectile, the term body has come to be applied specifically to the cylindrical portion between the bourrelet and the rotating band. Its diameter is less than that of sections immediately in front and in rear to prevent contact with the rifling. The diametral clearance should be a minimum, consistent with ease and economy of manufacture, in order to provide maximum capacity with necessary strength. The walls must be carefully designed to withstand the stresses to which subjected; the thickness at each section depends upon the material employed, the type of projectile, the nature and magnitude of the stresses, and the strength required. The length of the body of the projectile has been increased to secure increased weight and capacity and improved ballistic performance. The entire projectile should be streamlined to the greatest practicable degree to lessen air resistance; its center of gravity should be so located, and the projectile balanced accurately without eccentricity, to insure the best attainable flight characteristics.

Cavity.—The size, shape, and longitudinal location of the cavity are important design features. In general, it should be of the greatest practicable capacity, consistent with requisite wall strength, to permit

use of the maximum high explosive, chemical, shrapnel, or other filler. It will vary therefore with the type of projectile and the use for which designed and, in any particular projectile, the cross section will vary along the axis. Difficulties in manufacture and loading must be considered in connection with the design. An interior contour with irregular or varying diameters, particularly where the opening in the base or head is smaller than the cavity, increases the difficulty and cost of machining and loading. Any eccentricity will result in impaired ballistic performance.

Thickness of Wall.—The maximum stress sustained in the gun by the wall of a projectile, at any section, is due to the pressure to which the wall is subjected in transmitting to that part of the projectile in front of the section the maximum acceleration attained. The maximum acceleration is due to the maximum pressure in the gun; and, this pressure being known, the acceleration is determined by dividing the pressure by the mass of the projectile. Thus

$$\alpha = \frac{P}{M} = \frac{Pg}{w}$$

where α is the acceleration; P, the maximum total pressure on the base of the projectile; and w, the weight of the projectile.

If we substitute in the equation the value of the maximum acceleration for α, and the weight of that part of the projectile in front of a given section for w, and then solve for P, the value obtained will be the maximum pressure sustained by the walls of the particular section.

The calculated unit stress with a suitable factor of safety applied must not exceed the stress corresponding to the elastic limit of the metal; nor must it cause excessive flexure in the walls of the projectile. If it does, the walls must be made thicker.

Thickening the walls will increase the weight in front of the section and therefore a new value of w must be obtained for a second determination.

In shrapnel it is desirable to make the walls as thin as possible in order to increase the number of bullets that may be carried. The longitudinal pressure of the contained bullets is borne by the base of the projectile, and the walls sustain only the pressure due to the centrifugal force and that proceeding from the weight of the head and fuze. Their thickness will therefore be determined by the requirement that they must resist rupture by the pressure exerted by the gases from the bursting charge when the head of the projectile is blown off. The pressure required to blow off the head is equal to the resistance offered to shearing by the screw threads and shear pins of the head.

The retardation when a shell penetrates an armor plate is much greater than the acceleration in the gun. Consequently, the stresses in the projectile are higher and a much greater thickness of wall is required than that needed to withstand the acceleration in the gun. As there is no means of accurately calculating the retardation at impact, the correct thickness of wall of armor-piercing projectiles cannot be calculated but must be determined by experiment.

By assuming that the plate offers a constant resistance to the penetration of a projectile, however, the thickness of wall necessary in the projectile to enable it to pass through the plate and have any required velocity on emerging may be determined. Thus, to determine the thickness of wall of an armor-piercing shell that is required to perforate an armor plate of given thickness and to have on emerging a certain remaining velocity, assume

v, the striking velocity.
v_1, the remaining velocity.
S, the constant resistance offered by the plate.
l, the thickness of the plate, in feet.
ρ, the constant retardation of the projectile during perforation.

The work performed by the resistance over the path l is equal to the energy abstracted from the projectile while passing through the plate. Then

$$Sl = \frac{M}{2}(v^2 - v_1^2)$$

$$S = \frac{M}{2l}(v^2 - v_1^2)$$

and

$$\rho = \frac{S}{M} = \frac{v^2 - v_1^2}{2l}$$

The pressure sustained by any section of the projectile during penetration is equal to the mass of that portion of the projectile behind the section multiplied by the retardation. Denoting by w' the weight of that part of the projectile behind any given section and by p, the unit pressure,

$$p = \frac{w'}{g}\frac{\rho}{\pi(r^2 - r_1^2)} = \frac{w'(v^2 - v_1^2)}{2lg\pi(r^2 - r_1^2)}$$

where r and r_1, the radii of the wall, have such values that p will not exceed the elastic limit of the metal for compression and the flexure of the walls will not be excessive.

Current practice in wall design is based upon experience and the results attained in experimental and service firings. Although theoretical calculations are of assistance in the preliminary phases of design, final acceptance of projectiles is based upon demonstrated performance. The use of alloy steels, heat treated to give the optimum physical qualities, is necessary in certain types to insure the requisite strength with the specified cavity volume.

Rotating Bands.—All artillery projectiles, except those for muzzle-loading trench mortars which are stabilized by use of fins, are equipped with rotating bands of relatively soft metal securely seated in the body. Gilding metal is employed for the banding of all projectiles for mobile artillery, antiaircraft artillery, and seacoast artillery under 6 in. in caliber. Copper bands are used for the larger calibers of seacoast artillery. As the projectile passes down the bore, the soft band is engraved by the lands of the rifling and the rotation necessary for stability in flight imparted. The band, which is slightly larger in diameter than the bore of the gun, and tapered at the forward end corresponding to the forcing cone at the origin of the rifling, performs the following additional functions:

a. Centers the rear of the projectile in the gun, and supports it in its travel through the bore. The only areas bearing on the lands are at the bourrelet and the band.

b. Locates the projectile initially in a fixed position, axially, in the gun, and holds it in place when the gun is elevated. This is necessary to secure uniform ballistics from round to round.

c. Acts as a gas check, preventing movement of the powder gases past the projectile.

For assembly, the band, which has an interior diameter less than that of the seat into which it is to be fitted, is expanded by heat, slipped over the base of the projectile, and forced into a machined undercut groove by use of a banding press. The undercut groove in the projectile is knurled or otherwise roughened to prevent slippage of the band due to stresses set up by the driving edge of the rifling. After assembly, the band is machined to final form and dimensions. The central section is generally cylindrical in shape, with annular rings or grooves to take care of excess metal displaced by the lands of the rifling. The front end is tapered to insure proper seating in the gun, and the rear usually has a raised lip to assist in centering the projectile initially and as a gas check.

The displacement of band metal due to engraving and compression must be provided for in the design; otherwise *fringing* will result, the excess metal being forced to the rear of the band and, under the action

of the powder gases and centrifugal force, forming an irregular skirt or fringe. Excessive or irregular fringing affects flight characteristics adversely, decreasing range and increasing dispersion. It can be prevented by proper design of the band and, when necessary, by cutting a groove in the projectile immediately in rear of the band to accommodate the excess metal.

The depth or thickness, width, number, and longitudinal location of bands depend upon the projectile, muzzle velocity, and type of rifling. Most of the available information on design is obtained by test firings and experiment; such formulas as are used are empirical, based upon observed results. The depth must be of sufficient thickness to *take* the rifling, fill up the grooves, and withstand the stresses at the moment of greatest angular acceleration. The width of the band is usually $\frac{1}{3}$ caliber in high-velocity guns, but less where lower velocities are to be used. In general, narrow bands give less dispersion than wide ones, but there is a minimum width necessary to impart the required rotational velocity and to prevent undue erosion due to escape of hot erosive gases. In some instances, two or more narrow bands are employed. The location of the band with reference to the base of the projectile, especially where boat-tailing is employed, appears to affect flight characteristics materially.

Base and Boat-tail.—The base of the projectile is that part in rear of the rotating band. The present practice is to employ a form which is cylindrical for a short distance immediately behind the band and then has a 5° to 9° taper for about $\frac{1}{2}$ caliber in length extending to the slightly-rounded base edge. The length and degree of the boat-tailing employed depends upon the projectile and the velocity. At velocities under that of sound, the boat-tail greatly reduces the retardation due to air resistance, increasing the range without increase in dispersion. Above the velocity of sound only moderate beneficial results are obtained and dispersion may be increased. Accordingly, the boat-tailing is effective in low-velocity weapons and in that part of the trajectory of high-velocity weapons after the velocity has fallen off to that of sound.

All artillery projectiles with explosive or chemical fillers are provided with metal base covers to prevent the hot propellent gases from entering through the threads of the base plug and base fuze, when employed, or through defects in the metal. For the larger shell a cup-shaped brass cover is used, with the edges fitted into a circular cut in the base of the projectile, and held fast by a ring of lead which is hammered in. (Figs. 312, 313, 314.) In certain smaller nose-fuzed shell a circular disc of brass or steel is attached by sweating or welding.

Summary of Projectile Data:

Weight, in pounds	$\frac{(\text{caliber in inches})^3}{2}$ (approx.)
Length	4 to 6 calibers
Length of head	$2\frac{1}{3}$ to 3 calibers
Shape of head	Ogival or conical
Radius of ogive	7 to 9 calibers
Width of bourrelet	$\frac{1}{6}$ caliber (approx.)
Width of band	$\frac{1}{3}$ caliber (approx.)
Length of cylindrical part of base	$\frac{1}{4}$ caliber (approx.)
Length of boat-tail	$\frac{1}{2}$ caliber (approx.)
Angle of boat-tail	5° to 9°
Ratio of filler to total weight	
Common steel shell	
Fragmentation type	10% (approx.)
Demolition type	15% to 20%
Chemical	10% to 15%
Armor-piercing shell	2% to 3%
Deck-piercing shell	5% to 8%
Shrapnel (filler of shrapnel balls)	40% (approx.)

347. Sectional Density of Projectiles.—It was shown in the chapter on exterior ballistics that the *retardation* of a fired projectile, caused by the resistance of the air, is inversely proportional to the *ballistic coefficient C*.

The value of C is determined from the equation

$$C = \frac{w}{id^2}$$

where w is the weight of the projectile, i is its coefficient of form, and d is its diameter. For a given velocity it is apparent that the retardation will increase directly with the square of the diameter of the projectile and inversely with its weight; or, more concisely, the retardation will increase directly with the fraction d^2/w.

The reciprocal of this fraction, or w/d^2, will therefore be the measure of the capacity of the projectile to resist retardation, that is, to overcome the resistance of the air. The fraction is proportional to the *sectional density* of the projectile, as sectional density equals w/Area.

The sectional density is of importance in considering the motion of the projectile in the air and in the gun.

Effect on the Trajectory.—The greater the sectional density of the projectile, the less is the value of its reciprocal, d^2/w, and consequently the less is the value of the retardation of the projectile.

Of two projectiles fired with the same initial velocity and elevation, the projectile with the greater sectional density will therefore lose its velocity more slowly and will attain a greater range. For any given range it will be subjected for a shorter time to the action of gravity and other deviating causes, and thus will have a flatter trajectory and greater accuracy.

The advantages of increased sectional density are, therefore, increased range, greater accuracy, and flatter trajectory.

The sectional density may be increased by increasing the weight of the projectile while keeping its diameter the same or by decreasing the diameter while keeping the weight the same. For projectiles of the same form, increasing the caliber increases the sectional density, since in this case w increases as d^3.

The weight of a projectile for a gun of any particular caliber may be increased by increasing its length. This has been done in modern projectiles for large guns until the length is from 4 to 6 calibers.

Increase in the sectional density of small-arms bullets is found in the tendency to reduce further the caliber of the shoulder rifle, the weight and diameter of the bullet being so reduced as to increase the value of w/d^2.

Effect on the Gun.—An increased weight of projectile will result in an increased maximum pressure in the gun if the same muzzle velocity is to be maintained with the same powder, size of powder chamber, and length of travel. The maximum pressure for any gun being fixed, the use of a heavier projectile will usually require a slower powder. If the increase in weight is very great, the size of the powder chamber or the length of the bore, or both, will have to be increased.

348. Classification.—The classification of artillery ammunition is based on the design of the projectile as influenced by the tactical use for which intended. The basic types are *shell* and *shrapnel*. A third type, *canister*, consisting essentially of a light metal case filled with steel or lead balls, and containing no explosive filler, is used to a limited extent. The term *shot*, formerly used to designate the thick-walled armor-piercing projectile with small explosive cavity, is no longer used. For training purposes, economy may dictate the use of cheaper *target* projectiles.

Service shell are classified further as *low explosive, high explosive, armor-piercing*, and *chemical*. The low explosive shell with a black powder bursting charge is used to a limited extent only in 37-mm. and 2.24-in. guns. Special types of shell, for which tactical requirements may exist in war, include *incendiary*, *tracer*, and *illuminating*. Shell for mobile and antiaircraft artillery are point fuzed, whereas, in the separate

loading ammunition for seacoast and railway artillery, the projectile is base fuzed.

349. High Explosive Shell.—Figure 313 illustrates a typical streamlined, point-fuzed high explosive shell. The fillers employed are TNT (standard) and amatol. The shell may be designed primarily for *fragmentation* effect, obtained through dispersion of the fragments at high velocity, or for *demolition* effect, produced by the blast and mining action of the high explosive charge; or its tactical use may require a combination of these effects. Fragmentation shell have fairly thick walls, a smaller bursting charge, and must be designed to yield complete and uniform fragmentation, with the pieces of effective size and weight.

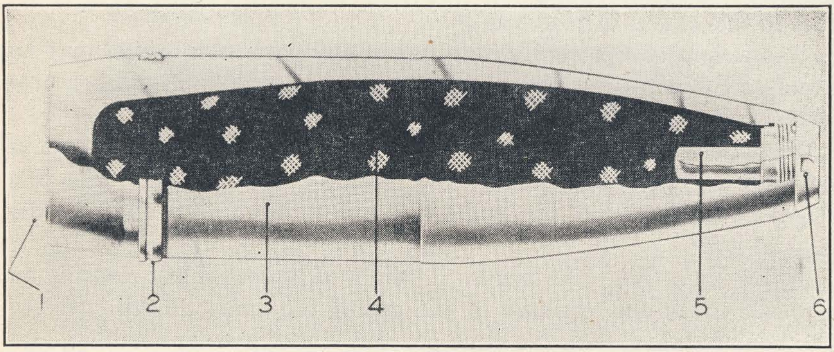


FIG. 313.—155-mm. High Explosive Shell, Mark I.

1. Base cover.
2. Rotating band.
3. Shell.
4. Bursting charge (TNT or amatol).
5. Booster.
6. Adapter.

When designed for demolition use, the wall is reduced to the minimum thickness consistent with requisite strength, and the bursting charge is made as large as possible. By the use of varying types of fuzes, a great variation in effect can be produced with the same shell.

High explosive shell, which is the normal type used by all mobile artillery weapons, has largely displaced shrapnel. It is effective against personnel, animals, field fortifications, and material targets, according to type, capacity, and characteristic action. Equipped with time fuzes, it is the principal type used by antiaircraft artillery.

350. Chemical Shell.—Chemical shell include all those filled with chemical agents designed to produce incendiary action, screening smokes, or physiological effect. Many types of agents may be employed based upon the action desired and tactical function. The filler may be solid or liquid.

The design of chemical shell differs but slightly from that of high

explosive shell in size, shape, and construction. Except for the special shell for the chemical mortar, it is used by the same field artillery weapons, and supplied, handled, and fired in the same manner as other shell. The threads in the nose are tapered to insure a gas-tight joint. The shell contains no more high explosive in the form of a *burster* than necessary to rupture it and disseminate the filler. Complete fragmentation of the case is not desirable, or essential, as in other types of shell, because of the undue dispersion of the filler and resulting loss in effective concentration. Chemical shell are equipped with nose fuzes of the impact type, designed for instantaneous or super-quick action, necessary to secure a burst above ground. The shell *burster* is of tetryl, or tetryl and TNT for the larger calibers, in the general form of the booster utilized in H. E. Shell.

351. Armor-piercing Shell.—The primary function of this type of shell is to penetrate the armor of ships and to explode inside. It is equipped with a delay-action base fuze. The shell and all components must be designed with sufficient strength to pierce armor plate approximately one caliber in thickness, at battle ranges, without breaking up, and in condition for effective delayed-action functioning within. To provide the requisite strength, the shell is constructed of forged alloy steel, heat treated to produce the best combination of hardness and toughness in each section. The walls are relatively thick, the explosive cavity is small, and extends only about half the length of the projectile proper as illustrated in Fig. 314. The bursting charge is explosive D, selected because of its ability to withstand the shock of impact against armor without premature detonation. The ogival head is rather short and blunt, as required for effective penetration. An armor-piercing cap is attached to increase its effectiveness against armor. A windshield or false ogive with a radius of approximately 9 calibers is added to reduce air resistance. Deck-piercing shell is a special type with thinner walls and correspondingly increased explosive cavity, designed for use in seacoast mortars and for plunging fire against the thinner deck armor of ships. The cavity of A. P. shell is closed at the rear by a heavy screwed-in base plug, which is fitted to receive the base fuze. Any possible entrance of hot powder gases is prevented by the base cover.

Armor-piercing Cap.—With the introduction of face-hardened armor, of alloy steel, heat-treated to produce a very hard face and tough core, the projectile of conventional design was defeated. The idea of fitting a special armor-piercing cap had been advanced in England as early as 1878, but it was not until 1894 that experiments in Russia against modern plate proved conclusively the superior penetrating power of the capped projectile.

The first cap was a short cylinder of soft steel fitted over the nose of the projectile and securely fastened by being pressed into an annular groove turned in the head before hardening. The modern cap is of the size and shape shown in Fig. 314. It is of forged alloy steel, decrementally hardened to insure a very hard face with a tough and relatively soft core in contact with the projectile. The skirt of the cap is peened at several places into notches cut in the head of the projectile. The windshield is attached to the cap as shown.

When an uncapped projectile strikes face-hardened armor, its whole energy is applied initially at the point, and the stresses induced are

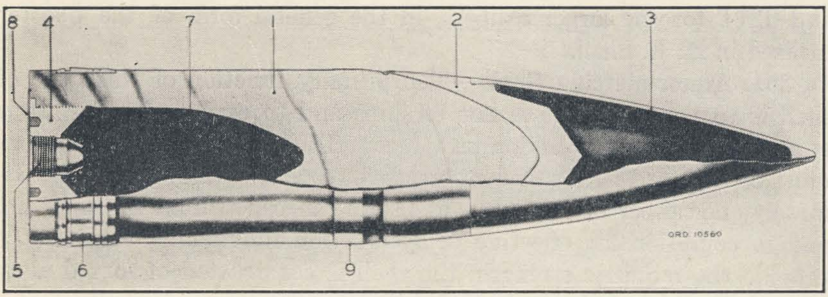


FIG. 314.—Armor-piercing Projectile.

1. Steel shell.
2. Armor-piercing cap.
3. Windshield.
4. Base plug.
5. Fuze.
6. Rotating band.
7. Bursting charge (explosive D).
8. Base cover.
9. Bourrelet.

greater than can be withstood in the small area. The result is that the point is shattered or broken off, the head flattened, and the projectile's penetrative power greatly lessened. On the other hand, when the projectile is capped, the pressure caused by the resistance of the plate is not confined to the small section at the point but is distributed over a larger area of the projectile. The hard face of the cap delivers a more effective shattering blow to the hard face of the plate than could the older type of soft cap, weakening the plate at the point of impact and breaking the way toward the softer backing. The hard point of the projectile proper reaches the severely strained armor undamaged, and the remaining energy is sufficient to penetrate the thickness of plate for which designed. The thickness penetrated depends not only upon the quality of the plate and the characteristics of the projectile, but also on the impact velocity and the angle of impact. The use of the A. P. cap greatly increases the *biting angle,* which is the angle measured from the normal, above which the projectile will ricochet instead of penetrate.

When the projectile strikes the armor, first the windshield and then the A. P. cap are broken up. The energy of the projectile acts through its center of gravity along the line of fire, and the resistance of the plate acts along the same line in an opposite direction. The forces acting may be resolved into components parallel to and perpendicular to the face of the plate. Unless the impact is so oblique as to result in ricochet, the couple acting parallel to the plate will tend to right the projectile toward the normal to the plate. This sudden tendency to right itself produces a bending stress on the body of the projectile. As penetration proceeds, another couple, resulting from the driving force of the projectile and the resistance of the jagged edges of the plate against the bearing side of the projectile, will tend to turn the axis back toward the line of fire. The base of the projectile on one side may be deeply gouged, cracked, or broken off. If complete penetration is secured, the hole will be of oblong shape when impact is oblique.

The forward part of the projectile must have adequate strength to withstand the stresses developed on impact and during penetration. It must be hard enough to insure satisfactory penetration, yet be sufficiently tough so that it will not crack or shatter. The cavity of the projectile is held well to the rear, not piercing the head. The body must be hard to withstand the gouging action of the edges of the hole, and of sufficient strength to withstand bending stresses. The base must have strength to smash through the plate if caught by the side of the hole, or be so designed that it can be stripped or gouged off without injuring the projectile. This latter feature has been attained in certain designs by use of a base ring of soft steel screwed on to the cylindrical portion in rear of the rotating band. This is readily stripped off if the projectile is caught in the hole.

352. Shrapnel.—The modern shrapnel is a projectile designed to carry a large number of spherical shot to a distance from the gun and there discharge them over an extended area. The common shrapnel for the divisional field gun is shown in Fig. 315. The body is a drawn-steel tube with a solid base. A diaphragm, supported by a shoulder, closes the base cavity for the bursting charge of black powder. The cavity above the diaphragm is filled with half-inch shrapnel balls composed of lead and antimony. The balls are held in place by a matrix of resin. The head, closing the forward end of the cavity, is screwed into the body. The combination fuze (time and percussion) is screwed into the head. The fuze is connected with the base charge by a central tube extending through the head and diaphragm.

Action of the Shrapnel.—When the gun is fired, the shock of discharge arms the fuze and ignites the powder train. This train can be adjusted

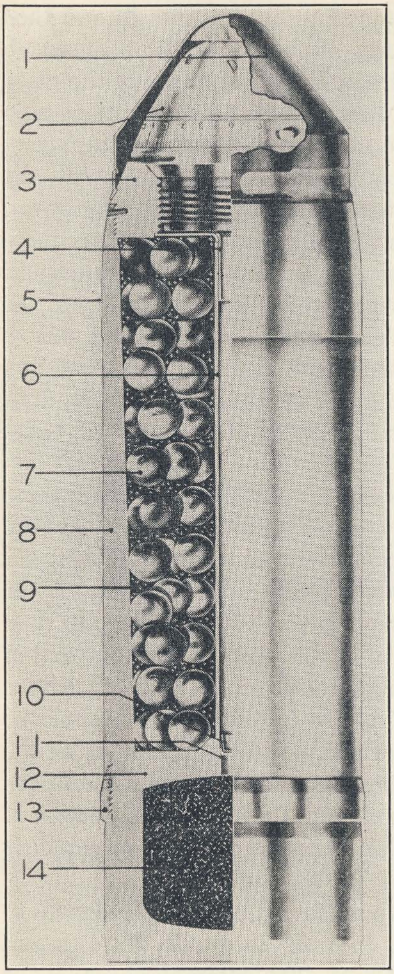


FIG. 315.—75-mm. Shrapnel.

1. Waterproof cover.
2. 21-second combination fuze.
3. Head.
4. Inner tube.
5. Bourrelet.
6. Central tube.
7. Balls.
8. Case.
9. Matrix (resin).
10. Fiber paper cup.
11. Cloth disc.
12. Diaphragm.
13. Rotating band.
14. Base charge (loose black powder).

to burn for a desired number of seconds, and is set to explode when the projectile has reached some predetermined point above and in front of the target. After the specified number of seconds, the time train ignites the magazine charge in the combination fuze and the flame passes down the tube to the base charge of the shrapnel. The explosion of the base charge does not rupture the case but ejects the diaphragm, balls, head, and fuze. The balls are projected forward with an increased velocity; and, because of the rotation of the projectile, they are dispersed also to the right and left. Their paths form a *cone of dispersion* about the prolongation of the trajectory. The pattern that this cone makes on the ground is an irregular oval with its longer axis in the plane of fire, as indicated in Fig. 316.

The explosion of the black powder base charge produces smoke and renders the shrapnel burst easily visible, so that adjustment of fire may be made from a suitable observation point.

353. Trench Mortar Ammunition.—Trench mortars are muzzle-loading weapons of relatively low power, designed specifically for high-angle fire. They may be smooth bore or rifled. The World War types of weapons were smooth bore, the cylindrical projectiles used were of the unstabilized type requiring an "always" fuze which would function regardless of how

the projectile struck, and the weapons were deficient because of the short range and lack of accuracy.

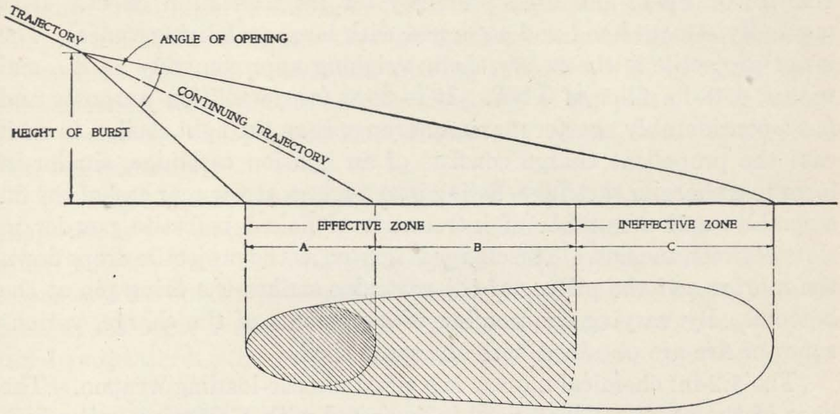


FIG. 316.—Ground Pattern, Normal Height of Burst.

Number of shrapnel balls striking in area A is approximately 50 per cent; in B, 35 per cent; in C, 15 per cent.

The present standard 81-mm. mortar is of the smooth-bore type, but employs stream-lined projectiles stabilized in flight by means of tail fins. Greatly increased ranges and improved accuracy have been

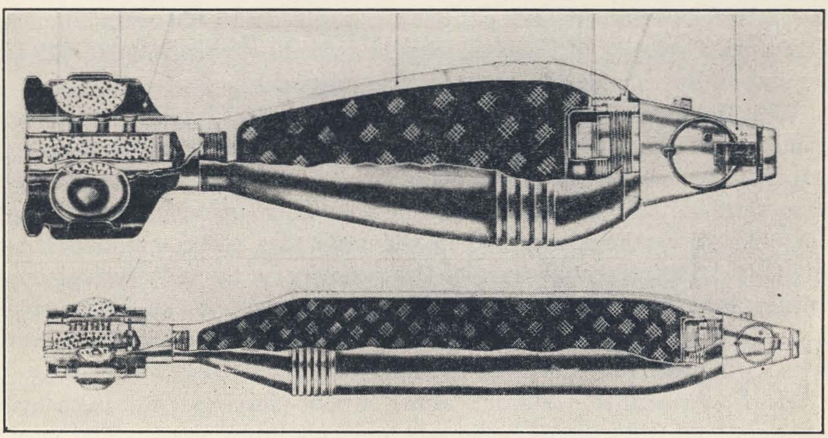


FIG. 317.—81-mm. H. E. Shell, Light and Heavy.

obtained. Three types of projectiles are provided, high explosive, smoke, and practice, all employing bore-safe, point-detonating fuzes. The two kinds of H. E. Shell used are shown in Fig. 317.

The projectile shown at the top of the figure is the light shell. It is a fairly thick-walled type, weighing approximately 7 lb., with a charge of 1.22 lb. of TNT, and used primarily for fragmentation effect. It is markedly stream lined and equipped with large stabilizing vanes. The lower projectile is the heavy shell, weighing approximately 14 lb., and with a 4.48-lb. filler of TNT. It is used for demolition purposes and has a considerably shorter maximum range than the light shell. In each case the propellent charge consists of an ignition cartridge, similar in form to a shotgun cartridge, fitting into a recess at the rear end of the fin assembly, and a number of increments of flaked ballistite powder in slots between the fins. The charge is ignited as the projectile drops down the mortar and the primer of the cartridge strikes the firing pin at the bottom. By varying the number of increments of the charge, various zones of fire are obtained with the same shell.

The 4.2-in. chemical mortar is a rifled muzzle-loading weapon. The base of the chemical shell used is equipped with a rotating unit which includes a cup-shaped annular disc of soft metal, of the same diameter as the shell body. Under the action of the powder gases, transmitted through a pressure plate, the flange of the disc is forced outward into the rifling, performing the same function as the rotating band of other projectiles. The propelling charge consists of a 90-grain ignition cartridge inserted into a container at the base of the shell, and the propellant proper of nonhygroscopic powder in the form of thin discs which fit over the cartridge container. The powder is assembled into 150-grain bundles. The muzzle velocity of the shell may be varied between 200 and 575 ft. per second by varying the number of bundles used.

354. Projectile Manufacture.—Service projectiles are produced usually from the best quality of forged steel, which must be homogeneous and free from seams, pipes, and other defects. Whether plain carbon or alloy steel is used, and the chemical composition thereof, depend upon the physical qualities required in the projectile. The manufacturing methods differ greatly because of the variety of sizes and types of projectiles, the materials used, and the contractor's equipment. Semi-steel is used to a certain extent. Considerable experimentation has been done with drawn seamless steel tubing.

A. P. Projectiles.—Major caliber armor-piercing projectiles are manufactured from forged high carbon nickel-chrome steel. The specifications may cover precisely all details of the design, but normally cover only the essential shapes, dimensions, and locations, leaving to the contractor the completion of the design according to his own ideas and experience. The chemical composition, heat treatment, and method of manufacture are not prescribed, although uniformity within a lot is

required. Acceptance or rejection is based upon the results of tests of representative samples. For acceptance, satisfactory results must be obtained from flight and fragmentation tests and, in addition, ballistic samples must be able to pass through standard armor of given thickness, at specified angles of impact and striking velocities which depend upon the caliber of the projectile and the thickness of the plate. The recovered projectiles must be intact, structurally sound, and in effective bursting condition.

The ingot is cast head down in an iron mold. If the cavity of the projectile is to be *bored out*, the ingot is made larger in diameter and much shorter than the finished projectile, being lengthened and the diameter reduced as it is forged to exterior shape. If the cavity is to be *pierced*, the ingot is cast in a mold having the same contour as the finished projectile but of smaller diameter. If the ingot is to be rough-

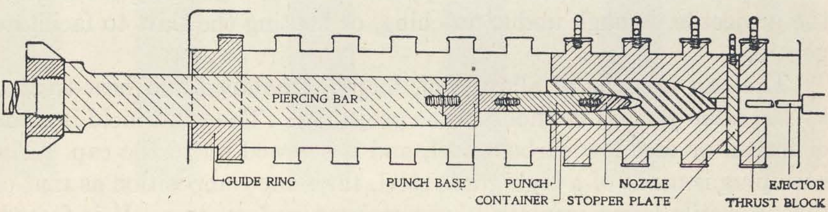


FIG. 318.—Fixture for Shaping and Punching Large Shell.

turned before forging, to remove scale and surface defects, it must first be given a preliminary anneal.

For the piercing operation, a fixture such as shown in Fig. 318 may be used; the die or container has been accurately bored to the proper contour. The ingot is brought to a forging heat of about 1100° C., pressed into the die, and pierced by the nozzle of the punch which is actuated by the piercing bar of the hydraulic press. In the process, the plastic metal is forged against the walls and point of the die, and surplus metal is forced through the hole in the point.

The rough forgings are then annealed, to normalize the structure and to soften the metal for machining. The principal machining and other finishing operations are:

1. Center, mount in lathe, and rough-turn head, body, and base, using a special fixture to obtain the desired contour of ogive; cut off discard at base.

2. Rough-bore and finish-bore the cavity on a boring lathe.

3. Finish-turn projectile to final size except the bourrelet which is left about 0.015 in. oversize for subsequent accurate grinding.

4. Face the base, counter-bore rear end of cavity, cut groove for base cover, cut threads at base of cavity for base plug, mill notches in head for attaching A. P. cap.

5. Heat-treat. The hardening and subsequent drawing operations are designed to give the best combination and distribution of physical qualities in each section of the projectile. The temperatures employed, the quenching media, and the procedure will vary with the type of steel, and the results sought by the contractor. The head of the projectile is made very hard, with the hardness decreasing and toughness increasing from bourrelet to base.

6. Grind bourrelet accurately to finish dimensions.

7. Cut and score rotating band seat, press on band, and turn band to prescribed form and dimensions.

8. Assemble base plug, fuze plug, and cap and windshield together. The cap must be attached securely, and without weakening the head of the projectile through undue notching, or heating the skirt to facilitate peening.

The cap is made of alloy steel, forged, machined and heat-treated by the same general methods as the projectile. The windshield is made of forged or cast low carbon steel, and is screwed on to the cap. The base plug is made of a high-grade steel, the same composition as that of the projectile being employed by certain manufacturers. It is forged, machined, and heat-treated substantially by the same operations as the projectile. The fuse hole plug is made by machining ordinary bar stock.

Other Projectiles.—Projectiles other than those designed for armor piercing are made from simple carbon steel. The smaller sizes are made from bar stock which can be machined to proper size and shape on screw machines or turret lathes. For calibers larger than about 75 mm., billets are cut from bars or forged from sliced ingots, the billets are forged in a die and the cavity punched, and then machined, heat-treated, and assembled. The following is a brief description of one method, of which there are many, of manufacturing 75-mm. shell. (Fig. 319).

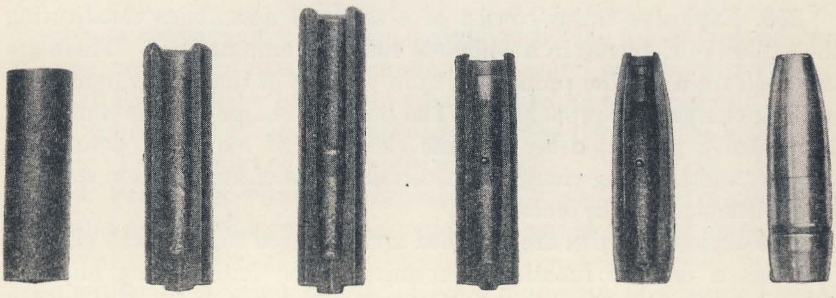
The billet or blank *A* is punched in one or more operations to the form *C*, and then transferred to the machine shop. The principal finishing operations include (1) center and rough-turn body; (2) bore cavity and cut to proper length; (3) finish-turn body; (4) face and square base; (5) heat head and *nose-in* to proper form, as in *E*, in forging machine; (6) heat-treat; (7) finish-turn head; (8) cut groove for rotating band; (9) grind bourrelet; (10) press on rotating band; (11) cut threads in nose for fuze; turn rotating band to prescribed shape and dimensions.

The sequence of operations, and the methods employed, depend not

only upon material, type, and size, but also upon the manufacturer's equipment and processes.

355. Loading of Projectiles.—The projectile is transferred to the loading plant to receive its filler of low explosive, high explosive, or chemical agent. The low explosive (black powder) charge is used to a very limited extent in certain types of the smaller service shell, as the expelling charge in shrapnel, and to a considerable extent in practice shell. The loading of the various types of chemical agents will not be discussed.

Ammonium Picrate.—The reason for the adoption of Explosive D for A. P. projectiles has been stated. Its use presents loading diffi-



A B C D E F

FIG. 319.—75-mm. Shell.

culties; it cannot be melt-loaded since it decomposes at or below its melting point. It is loaded in increments, each of which must be pressed or rammed by the use of hydraulic presses, or drop hammers, before the next increment is added. A uniform density of not less than 1.45 is necessary in order that the *set-forward* of the charge on impact against armor may not result in a cavity in the rear in the vicinity of the fuze, sufficient to cause malfunctioning. All A. P. projectiles are now arsenal-loaded.

Trinitrotoluene.—TNT is loaded by melting and pouring or casting into the shell cavity. It is poured at a temperature just above its crystallization point (about 80° C.) to minimize the amount of contraction and cavitation, and to reduce the time for cooling and solidification. The average density specified for cast TNT is 1.55. By the use of a certain part of the charge in the form of solid pellets, the loading operation may be speeded.

Amatol.—The loading of amatol depends upon the proportion of ammonium nitrate and TNT employed. The 50–50 amatol is sufficiently fluid when hot to be poured, as in TNT loading. The 80–20

mixture is plastic but not fluid; this is because of the small proportion of TNT, the only fluid ingredient, the other being in the form of dry powder. This mixture may be loaded by tamping or by use of an extrusion apparatus. A density of approximately 1.40 is specified.

Tridite.—This mixture of 80 per cent picric acid and 20 per cent dinitrophenol is loaded by pouring as in TNT loading. The addition of the 20 per cent dinitrophenol reduces the melting temperature from 120° to 90° C., thus permitting the use of low-pressure steam for the melting. The density obtained is approximately 1.64.

EXPLOSIVE TRAINS

356. Explosive trains consist of a series of assemblies constituting the explosive elements in a complete round of ammunition. There are two such trains. The propellent train consists of the primer, igniter or igniting charge, and propellant. The bursting charge train is composed usually of a primer, delay or time elements (if required), detonator, booster, and bursting charge. In certain types of ammunition some of these elements may be omitted.

The explosive trains are designed and arranged so that each element performs a definite function, transmitting the initial firing impulse, through successive steps, until the projectile bursts with the desired effect at the designated point or time. The malfunctioning or non-uniform functioning of any element affects the performance of the whole. In general, the system is arranged so that the successive impulses are transmitted by small quantities of more sensitive explosives to larger quantities of less sensitive explosives. The system must be safe, certain in action, and uniform in performance.

PRIMERS

Primers are employed to supply the initial impulses in explosive trains for the ignition of propelling charges (propellent primers) and the explosion of bursting charges (fuze primers). Primers should be certain and uniform in functioning, safe to use and handle, stable under normal storage conditions, and, within attainable limits, simple in construction, readily procured or manufactured, and as cheap as possible. The essential element of a primer is a sensitive explosive or explosive mixture, which can be ignited readily by simple means. Other less sensitive explosives such as black powder may be employed to step-up the initial flame.

357. Propellent Primers.—Propellent primers are classified in accordance with the method by which they are fired, as *percussion,*

friction, *electric*, *combination*, and *igniting* primers. The introduction of colloided nitrocellulose powders, and of modern FNH powders, which are relatively difficult to ignite, the employment of different granulations, sizes, compositions, and types of charges, and their use in chambers of varying shape, capacity, and dimensions, necessitated the development of special ignition systems. Complete and uniform ignition is essential for uniform ballistic performance. The action of the primer, with its associated black powder igniter, affects the maximum pressure, the velocity, the amount of muzzle flash, and the time interval between the application of the initial impulse and the expulsion of the projectile from the muzzle. The ideal ignition system would ignite each grain of the propelling charge completely and simultaneously. Although impossible of attainment, this is approximated by the use of long primers of large capacity in fixed ammunition, and short primers with supplementary black powder igniters in separate loading ammunition.

All primers are affected by moisture. Excessive moisture may cause failure. They should be stored in a dry place.

358. Percussion Primers.—Percussion primers are used in all service fixed and semi-fixed ammunition, and in separate loading ammunition employed by mobile artillery. The size and capacity depend upon the ammunition for which designed. Except in the case of separate loading ammunition, the primer, of slightly larger diameter than the seat, is inserted into a seat in the base of the cartridge case with a *force fit* by means of a press. In certain larger calibers, a close-fitting threaded joint has been employed. In either type, the primer case must be securely held to prevent setback due to the action of gas pressure, and must have a positive seal to prevent the leakage of gas. The primer base must have such thickness and physical qualities as will insure action of the primer mixture under the blow of the firing pin, and yet not be punctured by the blow. To secure uniformity of the percussion blow, an auxiliary firing pin or plug may be incorporated in the primer. (Figs. 320 and 322.) In other types, the firing pin blow falls directly on the primer cap. (Fig. 321.)

The percussion pellet of sensitive explosive or explosive mixture is forced against the anvil by the blow from the firing pin, and exploded. The flame passes through vents in the anvil into the body of the case, igniting the black powder. The walls of the shorter primers, with relatively small amounts of black powder, are not perforated and the flame is transmitted to the charge through the front end. (Figs. 320 and 321.) The longer primers, which fit well into the propelling charge, have holes in the walls to facilitate the transmission of the flame. (Fig. 322.)

The 49-grain percussion primer shown in Fig. 320 is a French type employing an auxiliary firing pin. This was necessary because of the

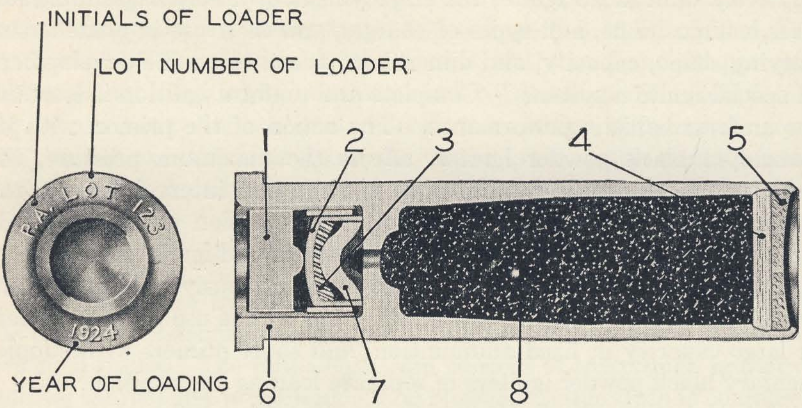


Fig. 320.—49-grain Percussion Primer.

1. Firing plug.
2. Cup.
3. Composition pellet.
4. End closing wad.
5. Shellac.
6. Body.
7. Anvil.
8. Black powder.

construction and action of the firing pin in the firing mechanism of the 75-mm. Gun, Model 1897.

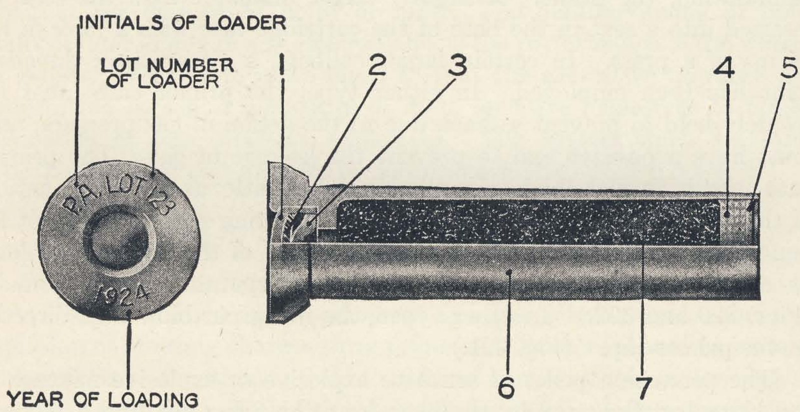


Fig. 321.—21-grain Percussion Primer.

1. Percussion cup.
2. Percussion composition.
3. Anvil.
4. Wax.
5. Shellac.
6. Case.
7. Black powder.

The 21-grain primer, generally similar in design but without the auxiliary firing pin, was designed for use with separate loading ammunition in the 155-mm. howitzer, 155-mm. gun, and 240-mm. howitzer.

These weapons are equipped with percussion type firing mechanisms, containing a primer holder into which the primer is inserted. The use of black powder igniters assembled to separate loading propelling charges permits use of a smaller black powder charge in the primer.

Two of the newer types of primers are shown in Fig. 322. These primers, which are of much greater length than formerly, are designed to ignite the propelling charge near the center and to spread the flame over considerable area by forcing it out through perforations in the primer body. Figure 322 (*A*) shows a 100-grain primer which is representative of the types now generally used in fixed ammunition. The primers for the various calibers differ only in size and in quantity of

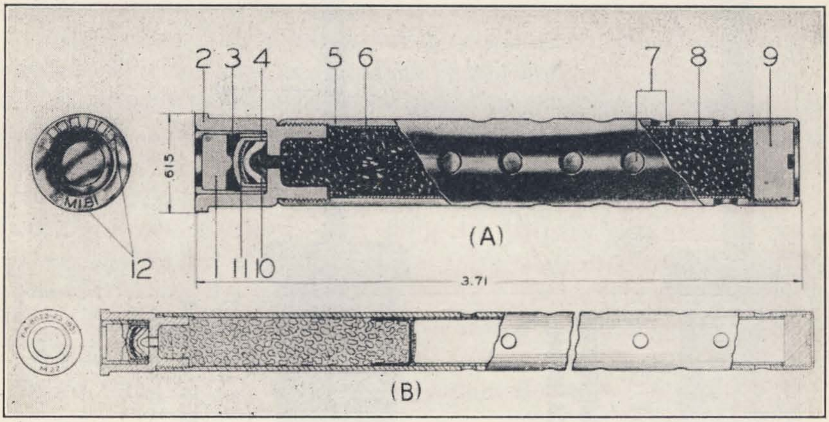


FIG. 322.—(*A*) 100-grain Primer. (*B*) 75-grain Primer.

black powder contained, the 37-mm. primer containing 20 grains and the 3-in. containing 330 grains. A newly approved standard for use with 75-mm. gun ammunition is shown in Fig. 322 (*B*). This primer contains 75 grains of black powder and differs from the preceding type by having only the front part of the body perforated and having the charge enclosed entirely in the unperforated base end. This permits the use of the correct amount of powder for the most efficient ignition and allows ignition to take place only in the vicinity of the center of the charge.

359. Electric, Friction, and Combination Primers.—These are the types used in seacoast cannon using separate loading ammunition. The primer is inserted in the vent of the obturator spindle attached to the breechblock and is held in position by the firing lock mechanism. Types of these primers are shown in Fig. 323.

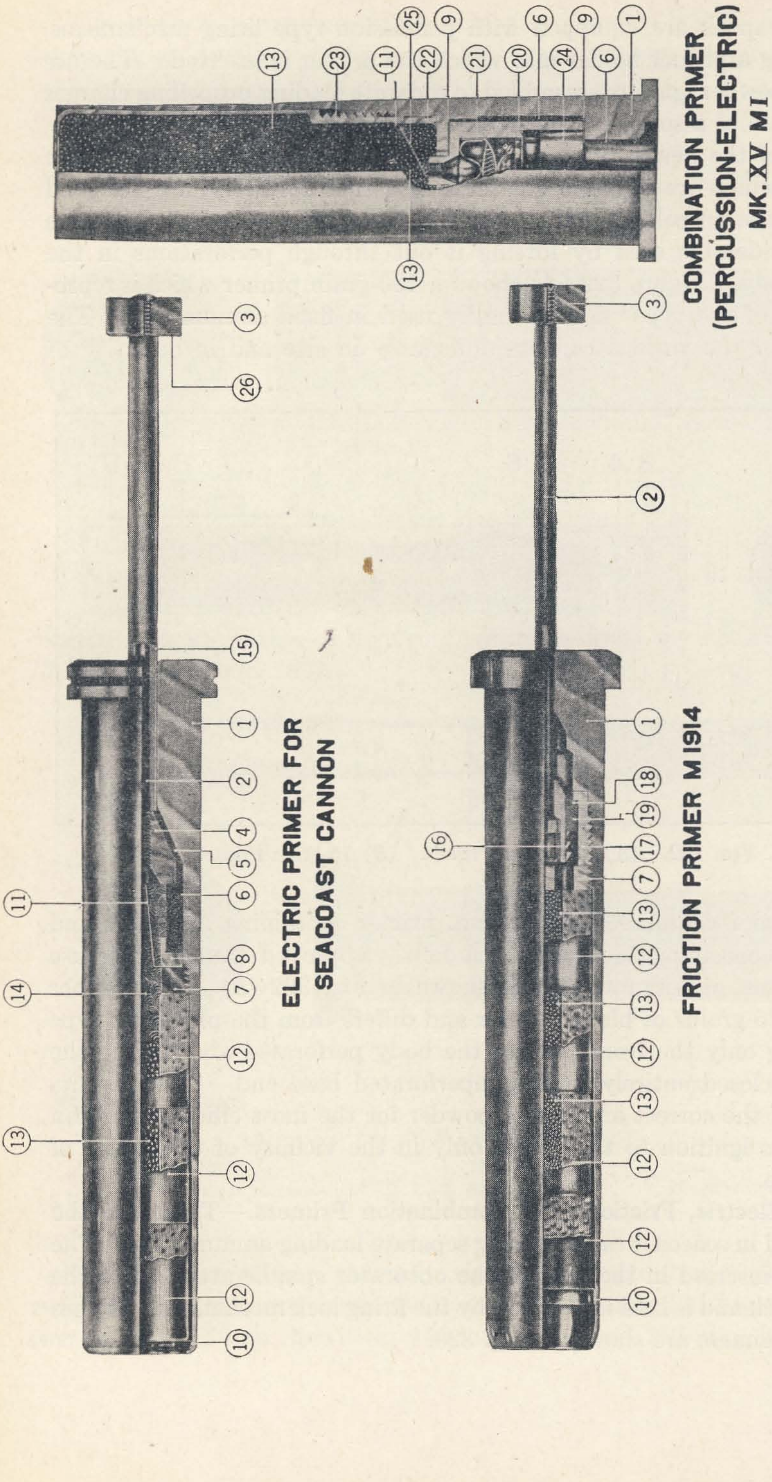


FIG. 323.

1. Primer Body.
2. Primer Wire.
3. Button.
4. Contact Plug.
5. Plug Insulator.
6. Insulator.
7. Closing Screw.
8. Contact Sleeve.
9. Insulating Disc.
10. Closing Cup.
11. Contact Wire.
12. Powder Pellet.
13. Loose Black Powder.
14. Fibrous Guncotton.
15. Paper Insulation.
16. Gas Check.
17. Housing.
18. Insulating Washer.
19. Friction Composition.
20. Plunger Cup.
21. Commercial Primer.
22. Ignition Cup.
23. Metallic Seal.
24. Plunger.
25. Wisp of Guncotton.
26. Paper Disc.

Electric Primers.—For electric firing, the contact clip on one wire of the firing circuit grasps the button of the primer wire, which is covered with an insulated paper cylinder. The wire is soldered to the fine contact wire, which is surrounded by fibrous guncotton. In firing, when the firing switch is closed or the magneto operated, the current passes through the wire to the contact wire, to the contact sleeve, to the primer body, and thence to the walls of the vent, the breechblock, the gun, and to the other lead of the firing circuit. The contact wire is heated sufficiently high to ignite the guncotton, which ignites, in turn, the loose powder and the powder pellets, which are thrown into the main charge in the chamber of the gun. The loose powder is more easily ignited than the compressed powder of the pellets and is used to facilitate ignition of the charge.

The primer body expands under pressure, and effectively seals the vent and prevents the escape of gas to the rear.

All electric primers should be tested prior to use for resistance and continuity of circuit. An electric primer testing set is provided for this purpose. Primers having a resistance over 3.0 ohms should be destroyed.

The Friction Primer.—For firing by lanyard, the friction primer is used. The leaf of the firing mechanism slips over the button of the primer. When the lanyard, attached to the leaf, is pulled, the wire is drawn to the rear, carrying with it the serrated gas check. The serrations are pulled through the friction compound, which is exploded, igniting the black powder and the powder pellets of the primer.

The Combination Primer.—The percussion-electric combination primer, as the name implies, combines the percussion and electric elements in one primer, as shown. In firing electrically, the circuit is from the contact piece, located in the hammer of the breech mechanism, to the plunger, thence to the percussion cup (commercial primer), to the plunger cup, to the contact wire, to the metallic seal, to the primer body, then to the gun and back to the source of current. The powder is ignited as in the electric primer.

In firing by percussion, the plunger is driven in by the blow of the firing pin and forced on to the percussion cup, exploding the percussion composition which ignites the loose black powder.

If the primer has failed electrically, it still may be fired by the blow of the firing pin. But the percussion element having failed, the primer cannot be expected to fire electrically.

A combination friction-electric primer is still used to some extent in service, though its manufacture has been discontinued.

360. Current for Firing Electric Primers.—Current from various sources has been used for firing guns electrically. The objection to taking the current from the electric wires connected with the power plant at the coast fortification is that these wires may be broken in action and that currents may exist in them when they are not expected to be present. Storage batteries and dry batteries have been used as the source of current, but these are subject to rapid deterioration and require constant care.

Special hand-operated magnetos are now furnished for all guns and mortars to be fired electrically. These magnetos are certain in action, require little care, and, since there is no voltage in the circuit except when they are operated, they afford the safest means of firing a gun electrically.

361. Igniting Primers.—Igniting primers are auxiliary primers assembled in fixed ammunition which is to be fired from subcaliber tubes in seacoast weapons not provided with percussion firing mechanisms.

The subcaliber guns are provided with fixed ammunition, into the cartridge cases of which the igniting primers are assembled. Igniting primers contain no friction or electric element within themselves, but they are ignited by the flame from the regular friction or electric primer placed in the vent of the breechblock in the same manner as for regular firing.

Igniting primers are provided with a priming charge arranged in the same way as for the regular primer. The flame from the regular primer, entering the igniting primer through the small opening, ignites the primer charge, which, in turn, ignites the subcaliber propelling charge. An obturating valve closes under the action of the pressure and prevents the escape of gases to the rear.

362. Fuze Primers.—Primers used to initiate the action of the bursting charge explosive train are usually set off by percussion. There are many types and sizes employed, but in general the primer consists of a very small quantity of a sensitive mixture enclosed in a small brass or gilding-metal cup. This cup is struck by the firing pin or striker which is actuated by set-back, impact, or spring action.

When used to ignite a delay or time element the primer must produce a nondisruptive flame, and it is necessarily of small proportions. Some explosive trains do not contain delay elements. In this case the primer is larger and ignites the detonator, or it may be actually combined with the detonator to give instantaneous action. The explosive train thus becomes entirely one of detonation rather than starting with combustion.

FUZES

A fuze is a mechanism for igniting or detonating the bursting charge of a projectile, and performs this function either upon impact or at a certain time during flight. When designed to function on impact it is classed as an *impact* or *percussion fuze*, and when designed to function at some predetermined time after the projectile leaves the gun it is classed as a *time fuze*. A *combination fuze* combines both time and percussion elements. It is normally set for time action but will function on impact should the time element fail or should impact occur before the time element causes functioning. Classed according to the assembled position in the projectile, there are *point fuzes*, which are assembled into the nose of shell, and *base fuzes*, which are assembled into the base.

Fuzes are further classified according to the action at the time of impact as *delay*, *non-delay*, *superquick*, and *supersensitive*. *Delay fuzes* are manufactured with various lengths of delay. They are designed to allow penetration of material targets before bursting the shell, or in some cases to obtain ricochet action when firing against personnel. They are always used in armor-piercing projectiles, to obtain complete penetration of the armor before the shell bursts. When fired for ground impact a large crater is obtained. *Non-delay* fuzes are designed to burst the projectile before complete penetration occurs. A rather small crater is obtained, most of the effect being above ground. This type fuze is used against matériel targets, lightly fortified positions, and to some extent against personnel. *Superquick* fuzes are designed to function before any penetration occurs, giving a maximum surface effect of the fragmentation. They are used against personnel, barbed wire and light matériel targets, and also in chemical shell to scatter the chemical entirely above ground. *Supersensitive fuzes* are designed to burst the projectile promptly on impact against a very light target, such as an airplane wing.

363. Requirements.—Fuzes should be certain in action, safe in handling and using, free from deterioration in storage, simple in design and operation, and easy to manufacture and load. Some of these requirements are conflicting, for example, safety features complicate the design and increase the difficulty of manufacture.

All fuzes used in our service are *bore-safe*, that is, they are arranged with safety devices which tend to prevent functioning until after the projectile has left the bore. In addition to being *bore-safe*, all recently designed fuzes in our service are *detonator-safe*. By this term we mean that the explosive train is interrupted between the detonator and the booster until the projectile has cleared the muzzle. In these fuzes a

premature explosion of the bursting charge is prevented even if the detonator should be exploded by shock or accident.

364. Methods of Arming.—The principal forces utilized in arming or preparing fuzes for action are *set-back*, the force of inertia or resistance to linear acceleration of the projectile, and *centrifugal force*, due to rotation of the projectile. In many designs both these forces are utilized for arming the fuze, thus increasing the safety. It is interesting to note that the force of set-back exists only during the time the projectile is in the bore, whereas centrifugal force exists from the time the projectile begins its movement until impact or detonation occurs. In some special fuzes, as in the supersensitive, the force of air pressure is utilized in arming. In all projectiles, the deceleration during flight produces a tendency for the fuze parts to creep forward. This force is known as *creep force* and special provisions must be incorporated in many fuzes to prevent this force causing either malfunctioning or premature functioning.

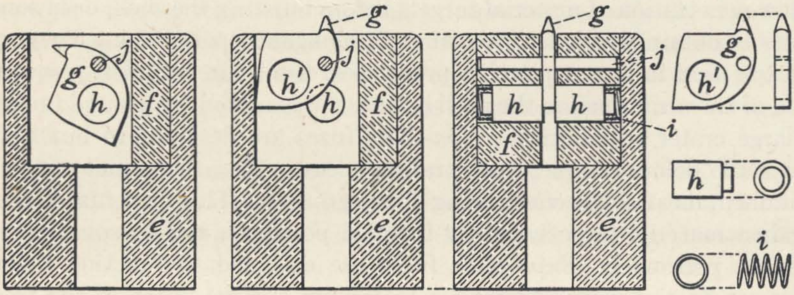


FIG. 324.—Semple Centrifugal Plunger.

Semple Centrifugal Plunger.— A typical example of an arming mechanism used in many American fuzes is the Semple centrifugal plunger, illustrated in Fig. 324. Although this plunger is operated primarily by centrifugal force, it also makes use of the force of inertia to provide the *bore-safe* feature and to insure safety in transportation and handling.

The firing pin, *g*, is mounted on its fulcrum, *j*, in a slot in the plunger body, *f*. In the unarmed position of the firing pin, each safety pin, *h*, is pressed by its spring into a hole in the firing pin and prevents its rotation. A side blow which might compress one spring and permit the pin to leave the hole would tend to make the opposite pin remain in the hole. For this reason it is practically impossible for the fuze to arm itself in transportation.

Operation.—When the projectile has attained a certain velocity of

rotation, equal to or greater than that for which the safety pin springs, *i*, are designed, the centrifugal force causes the safety pins to compress their springs and leave the hole in the firing pin. The firing pin is then free to turn about its fulcrum. Its weight is so disposed with reference to the fulcrum that centrifugal force will tend to turn it about the fulcrum and arm it. However, if there is any considerable longitudinal acceleration of the projectile, which is the condition until it leaves the muzzle, the disposition of weight of firing pin with respect to the fulcrum is such as to cause a turning effect opposite to and greater than that caused by centrifugal force. This feature prevents the firing pin from arming until the projectile has left the gun. A possible cause of the bursting of projectiles in the gun is thus removed. Once armed, the same disposition of weight with relation to the pivot and the forces acting tend to keep the firing pin in the armed position.

After the projectile leaves the gun, it is subject to retardation due to the resistance of the air. The plunger, not being subject to this resistance, tends to creep forward and place the firing pin in contact with the primer. To prevent this, two restraining springs not shown in the figure are placed between the forward end of the plunger and the fuze housing.

SERVICE FUZES

A description of several types of service fuzes will illustrate the principles of design and operation of this very important component of ammunition.

365. Point Detonating Fuze, Mark III.—The Mark III Fuze is superquick in action, and is employed with shell to produce great surface effect on a target, with the least penetration possible. The head of the fuze striking the ground about 0.0005 second before the ogive of the shell, immediately detonates the TNT charge and bursts the shell above the ground. The numerous steel fragments, traveling at high velocity, are very effective against personnel, matériel, and barbed-wire entanglements. This fuze also is used for gas and smoke shell. The construction of the fuze is shown in Fig. 325.

The body and small parts are of brass; the cap is of steel. There are three safety features: the brass spiral, the soft steel shear pin, and the centrifugal interrupter. The fuze is protected by a strip of friction tape wound around the head to keep the spiral in place. This is covered by a waterproof tin-foil hood.

The action is as follows: Before loading the shell into the gun the cover and tape are removed from the fuze by hand. After firing, the projectile moves down the bore with increasing linear and angular

velocity. The angular acceleration wraps the spiral more tightly around the firing pin, rendering the fuze *bore-safe.* Centrifugal force tends to move the interrupter outward against its spring pressure, but, the interrupter being set on an angle, this movement is prevented by inertia during the period of linear acceleration, or until the projectile clears the muzzle.

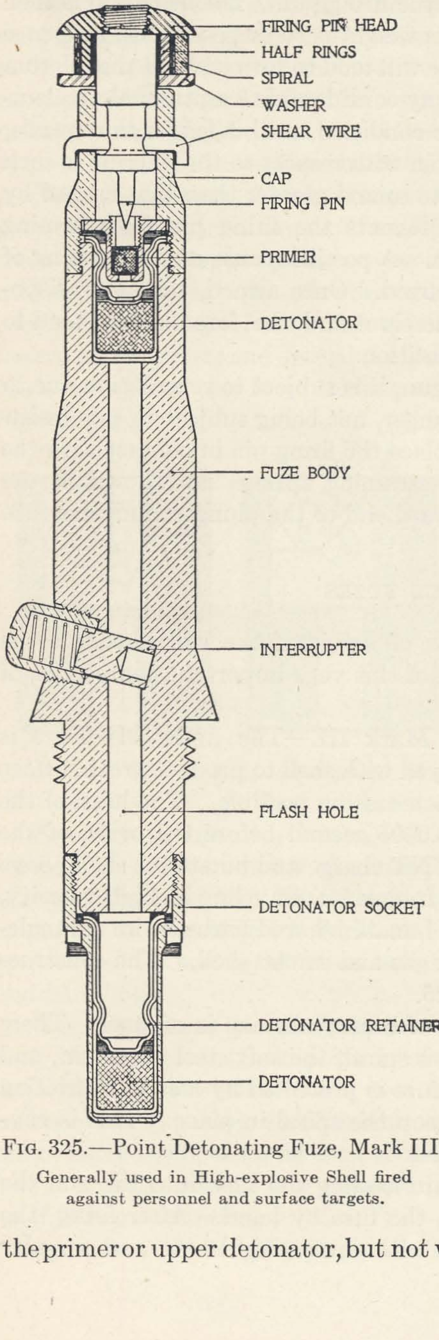


FIG. 325.—Point Detonating Fuze, Mark III.
Generally used in High-explosive Shell fired against personnel and surface targets.

When the powder gases cease to act on the projectile, the acceleration becomes negative and centrifugal force acting on the weighted end of the spiral causes the spiral to unwind and throw off the half rings, which are between the firing-pin head and the supporting washer. The interrupter is also thrown out, clearing the flash hole from the upper to the lower detonator.

The fuze, now clear of the bore, is armed; but the shear wire holds the firing pin away from the primer until the fuze head strikes the target. Impact then drives the firing-pin head back to the washer, shears the safety wire, and causes the firing pin to puncture the primer. The upper detonator thus ignited, the flame travels down the flash hole to the lower detonator, causing the detonation of the bursting charge of the shell.

This fuze is only partially *detonator-safe,* the interrupter making the shell safe with respect to accidental explosion of the primer or upper detonator, but not with respect to the lower detonator.

366. Point Detonating Fuze, Mark V.—The Mark V Fuze is of the "*delay-action*" type and is used when a slight delay action is required for penetration or for ricochet firings. This fuze gives a delay of approximately 0.05 second. Fuzes giving, respectively, non-delay and long

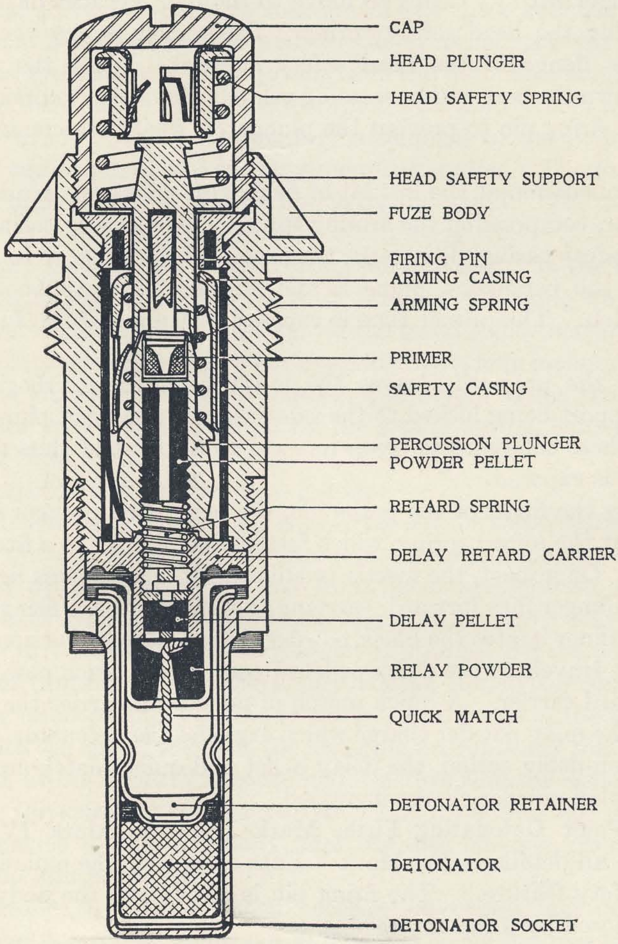


FIG. 326.—Point Detonating Fuze, Mark V.

(approximately 0.15 second) delay have also been manufactured. The time of the fuze action is varied by changes in the delay element.

The construction of the fuze may be understood by a study of Fig. 326. The arming spring, arming casing, and safety casing are placed concentrically around the percussion plunger. Each casing is provided with three prongs or clasp hooks. The percussion plunger is attached

to the delay retard carrier by the retard spring. The safety feature in the fuze head includes a safety spring, head plunger (lined with a casing with clasp hooks), and safety support covering the firing pin.

Action.—The concussion at the instant of firing causes the heavy head plunger with its casing to move to the rear, because of its inertia, compressing the head safety spring. The casing prongs then engage under the flange of the head safety support. While the projectile travels down the bore with increasing velocity, the safety support extends below the firing pin to prevent the plunger, if free, from coming in contact with it.

The concussion at the instant of firing also drives the arming casing to the rear, compressing the arming spring. The arming casing, sliding into the safety casing, disengages the prongs of the latter from the lower notch of the percussion plunger, and engages its clasp hooks in the upper notch. The primer thus is exposed. Arming of the fuze is now complete.

When the projectile leaves the muzzle, retardation begins. The safety support being locked to the safety spring and head plunger (with casing), these components creep forward as a unit and thus the firing-pin point is exposed.

During the flight of the projectile, the percussion plunger is held to the rear by the retard spring, which fastens the plunger to a fixed part of the fuze. On impact, the inertia is sufficient to distend this light spring and the plunger flies forward, carrying the primer to the firing pin.

The primer ignites the black powder pellet in the percussion plunger. The flame travels to the delay pellet of compressed black powder in the delay retard carrier. A quick match of guncotton carries the flame, in turn, to the relay powder charge which explodes the detonator.

For non-delay action, the delay pellet and quick match are omitted and the relay powder charge increased.

367. Point Detonating Fuze, Mark IV.—The Mark IV Fuze is similar in all details to the Mark V Fuze except for the omission of the "head safety feature." The firing pin is screwed to the body and the head is closed by a flat screw plug.

368. Point Detonating Fuze, Model T3.—The Point Detonating Fuze, Model T3, illustrated in Fig. 327, is a selective superquick or short-delay fuze; that is, it may be set to function instantaneously on impact with the target or 0.05 second after impact. This fuze, or one of similar design, will replace the Mark III, Mark IV, and Mark V point detonating fuzes, with their adapters and boosters, where used in high-explosive shell. The T3 fuze is detonator-safe; that is, the booster charge will not detonate even if the detonator and delay elements are exploded. This

safety feature is obtained through the use of a rotor, a metal disc about 3/8 in. thick containing the combination primer-detonator. The axis of rotation of the rotor is not in line with the axis of the fuze, and part of the periphery is cut away in such a manner that, at the proper time, centrifugal force will produce rotation of the rotor sufficient to bring the detonator into alignment with the delay pellet and tetryl channel leading to the booster. Prior to this time the detonator is out of alignment and the explosive train is interrupted by a solid part of the rotor.

This fuze is issued to the battery assembled to the shell, with the shipping cap in place, and set for superquick action. The cap must be removed prior to setting the fuze and firing the round. The fuze will not function unless the cap is removed.

The cap holds the superquick firing pin in a cavity in the rotor, thus preventing any possibility of the rotor rotating or arming while the cap is in place. This cap is in addition to the usual safety features of fuzes and permits severe handling, such as rolling down long inclines in loading on cars or transports, without danger of arming. When the cap is removed, the striker head is lifted by the striker spring, thus raising the firing pin from the rotor.

The operation of the fuze is as follows:

(*a*) *Action in the Bore of the Gun, Fuze Set for Superquick Functioning.*—In the bore of the gun, the fuze parts are acted upon by centrifugal force and by the forces resulting from linear acceleration (set-back). The set-back causes the superquick firing pin to move rearward with reference to the fuze. This movement is stopped by the striker head coming in contact with a sleeve surrounding the striker spring. The firing pin enters a small hole in the rotor. As the axis of the rotor is not in line with the axis of the fuze, the firing pin prevents any rotation of the rotor and, as far as safety is concerned, the fuze is in the same condition as before the shipping cap is removed. The rotor thus has no rotation with reference to the fuze body, and the fuze emerges from the bore of the gun still unarmed.

(*b*) *Action in Flight.*—When acceleration ceases and deceleration begins, the superquick firing pin is returned to its original position by the spring, which serves now to resist air pressure against the striker head. At the same time, centrifugal force causes the centrifugal pins to fly out against the force of their restraining springs and thus disengage the delay plunger and the rotor. The rotor swings counterclockwise with reference to the rotating projectile until stopped by the stop pin. In the new position, the detonator is directly in line with the superquick firing pin and with the tetryl channel which leads to the booster charge.

(*c*) *Action on Impact.*—On satisfactory impact, the striker head is

retarded and the firing pin is driven instantly into the detonator, which explodes, detonating the booster charge and, in turn, the explosive charge of the shell. Detonation of the explosive charge of the shell actually occurs before the nose of the shell has struck the target.

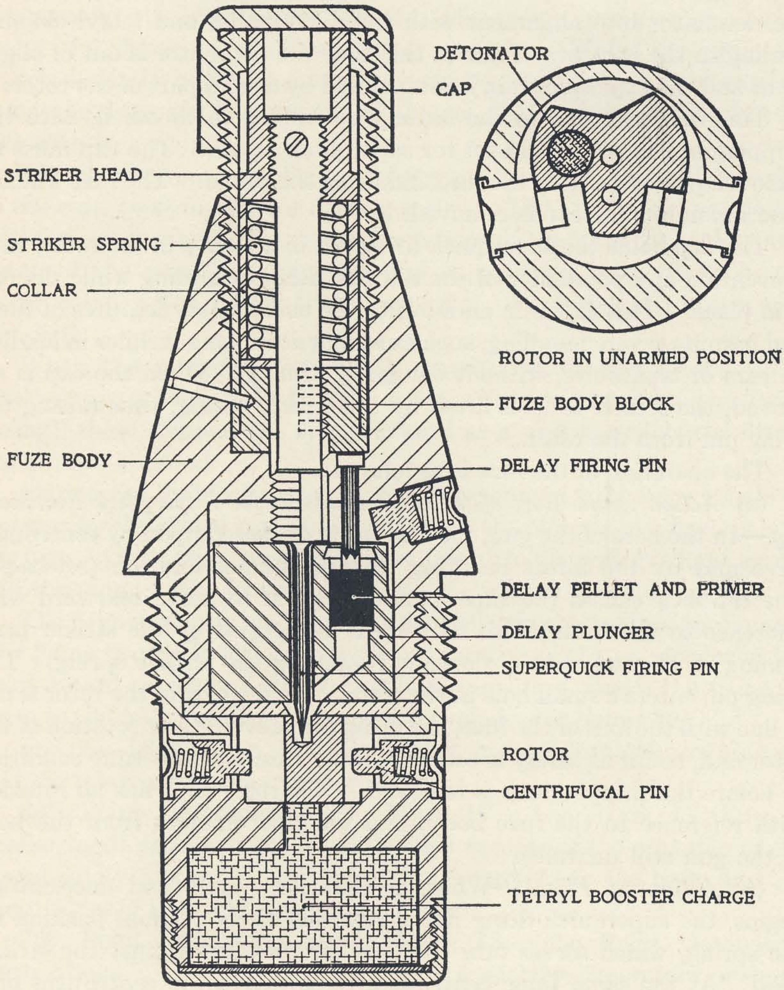


Fig. 327.—Point Detonating Fuze, Model T3.

Should the character of impact be such that the striker head is not operated, the fuze will function with delay action.

Short Delay Action.—To set the fuze for short-delay action, the striker head is turned clockwise, as viewed from the top, as far as

possible. The superquick firing pin is now raised and its lower threads are engaged with threads cut in the fuze body block, fixed to the fuze body, thus rendering the superquick firing pin inoperative. The functioning of the fuze when so set is as follows:

(*a*) *Action in the Bore of the Gun.*—While in the bore of the gun, the accelerating forces are greater than the centrifugal forces, and the fuze emerges from the bore still unarmed.

(*b*) *Action in Flight.*—The arming of the fuze is the same as described for the superquick setting, except that no movement of the striker head and superquick firing pin takes place.

(*c*) *Action on Impact.*—On impact with an obstacle, the shell and fuze are retarded. The delay plunger, being restrained only by light springs, travels forward, relative to the remainder of the fuze, and impact between the delay primer and the delay firing pin occurs. The delay primer is exploded. This action ignites the delay pellet, which burns through in about 0.05 second and explodes a small detonator in the delay plunger. The flame passes through the inclined communicating hole in the delay plunger on to the detonator in the rotor, detonating it. The booster charge then is detonated. This charge, in turn, detonates the main explosive charge of the shell. Superquick action cannot occur, as the stem of the superquick firing pin will collapse before the lower threads are sheared.

As assembled and shipped, the fuze is set for superquick action. The manner of setting for delay action has been previously described. To re-set for superquick action, the process is reversed, the striker head being turned counterclockwise until a sharp click is heard. The fuze setting can be changed any number of times. When the striker head is out as far as possible, the fuze is set for delay action. When the striker head is in as far as possible, the fuze is set for superquick action. A slot is provided in the end of the striker head to facilitate setting. A special setting tool is provided, but a screw driver or any similar tool, or the fingers, may be used.

369. The Supersensitive Fuze.—The supersensitive fuze is manufactured primarily to provide a fuze for the shell of small cannon fired from airplanes and against airplanes. It must be so sensitive that it will function promptly on impact with the fabric wing of a plane or the envelope of a balloon. The fuze represented in Fig. 328 depends for its safety in flight on the principle that the total air pressure acting on the *outside* of the striker head is opposed by a greater total air pressure acting *inside* the head.

The *body* of the fuze is bored out to form a cavity in which the *carrier* is screwed. The hollow fuze *head* is also screwed to the carrier. A longi-

tudinal hole extends through the carrier. The rear part of the hole contains a bronze cup in which are housed the *primer* and the *detonator*; the forward part embraces the *firing pin*, which extends through the *locking sectors* and is fixed to the *striker head*.

Ports are provided in a depression in the striker head to permit air to enter the inside cavity. The striker head is permitted a small movement

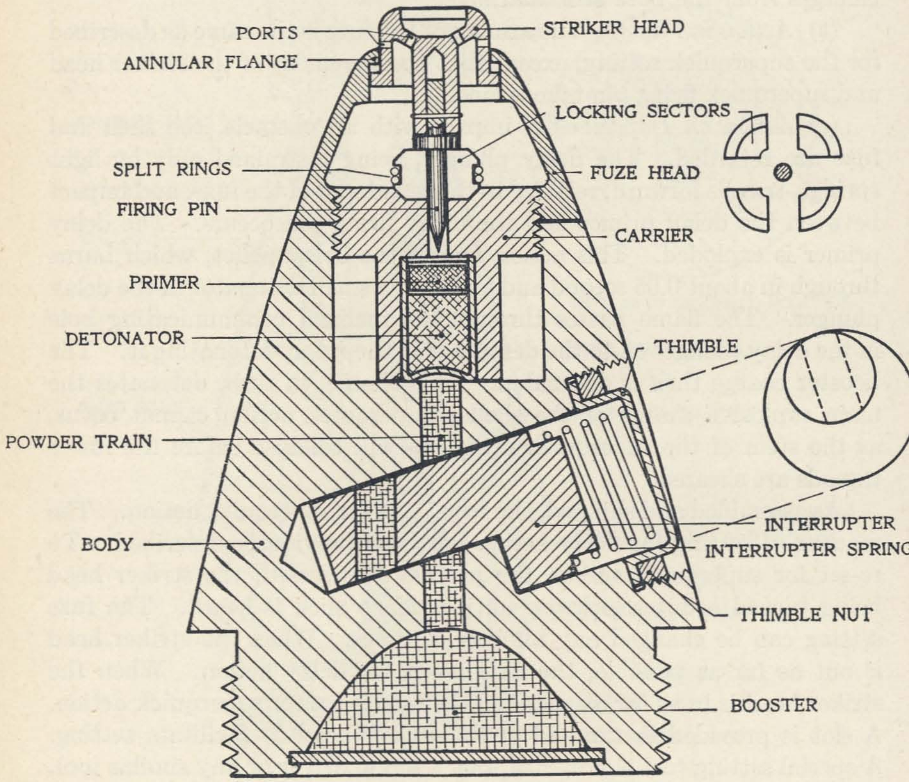


FIG. 328.—The Supersensitive Fuze.

to front and rear, which is limited by the annular flange and the locking sectors.

The firing pin normally is held away from the primer by a locking element, which consists of sectors of a brass cylinder arranged around the shaft of the firing pin and held together by light split rings. Linear acceleration, while the projectile is in the bore of the gun, causes the locking sectors to hug the bottom of their seat, resisting the centrifugal force tending to throw them to the walls of the fuze head. As soon as the projectile leaves the gun and linear acceleration ceases, the sectors

fly outward and the firing-pin point is free to come in contact with the primer.

The air pressure on the nose of the projectile in flight is very great, and tends to drive the striker head to the rear and the firing pin into the primer. The outside air pressure is sufficient to do this, were it not opposed by the air pressure developed beneath the striker head. The uniform interior pressure is as great as the maximum pressure on the exterior, and the cross-sectional area of the striker head which is exposed to the static air pressure on the inside is greater than the area exposed to the dynamic air pressure on the outside. The total static force is greater than the dynamic; and, during the flight of the projectile, the firing pin remains in its forward position.

When the striker head comes in contact with an object offering any appreciable resistance, the flow of air into the cavity is shut off, the firing pin is driven to the rear, and the primer and detonator are exploded.

The fuze is made detonator-safe by means of a centrifugally actuated interrupter, set on an angle, and carrying a connecting section of the powder train. The action of the interrupter in breaking the continuity of the explosive train until the projectile clears the bore is similar to the interrupter action of the Mark III Point Detonating Fuze previously described.

370. Combination Fuzes.—The combination fuze combines in one assembly independent time and percussion mechanisms. It functions in flight at the desired point in the trajectory through action of the time element which has been set for the corresponding time of flight, or on impact by action of the percussion element. It is the fuze used in service shrapnel. A straight time fuze, such as that used by antiaircraft artillery, has no percussion element.

The functioning of a fuze at a predetermined and set time may be accomplished either by mechanical means, as for example a clock mechanism, or by use of a slow-burning train of highly compressed mealed black powder. The combination fuze is a powder-train type; the proper length of delay, corresponding to the time of flight to the desired point of burst, is accomplished by a simple setting which varies the length of the time train to be burned.

The 21-second Combination Fuze.—The 21-second combination time and percussion fuze is illustrated in Fig. 329. It is a point fuze, issued assembled to the round. For protection in handling, and to prevent entrance of moisture through the open vent (15) leading from the time train, a waterproof cover (19) is provided which is removed at the gun before the fuze is set for the time or action desired. When issued, the fuze is set at *safe*, as seen in the right-hand illustration, indicated by

the symbol *S* of the graduated ring being positioned between the two datum lines above and below. By use of the fuze setter, the graduated ring may be turned to any time setting between 0 and 21 seconds.

The explosive action of the shrapnel is caused when the flame from the magazine charge of black powder (13) passes down through the central flash tube (6) (Fig. 315) to the base charge (14) (Fig. 315). The magazine charge itself may be ignited either by flame from the

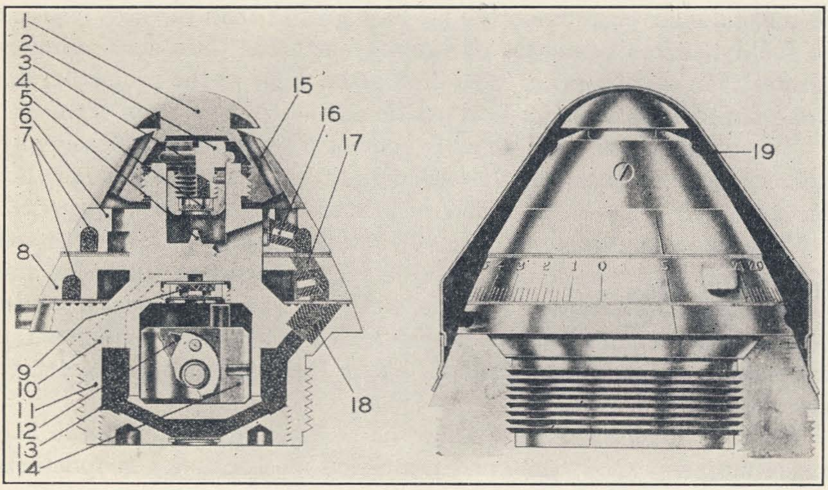


FIG. 329.—The 21-second Combination Fuze, Model of 1907M.

1. Closing cap.
2. Concussion plunger.
3. Resistance ring.
4. Concussion primer.
5. Concussion firing pin.
6. Upper time-train ring.
7. Powder train.
8. Lower or graduated time-train ring.
9. Percussion primer.
10. Channel.
11. Body.
12. Percussion firing pin.
13. Magazine charge (black powder).
14. Percussion plunger.
15. Vents.
16. Powder pellet.
17. Powder pellet.
18. Powder pellet.
19. Waterproof cover.

pellet (18) of the time element of the fuze, or from the percussion primer (9) through a channel (10).

The time train of the fuze is composed of two trains of mealed black powder (7) compressed in annular grooves cut in the bottom of the upper and lower time-train rings (6) and (8). The upper ring is fixed in position, whereas the lower or graduated ring may be turned to the setting desired. The grooves are not cut completely around the rings, a solid section of metal being left between the two ends in each ring and, consequently, neither powder train forms a complete circle. The

flame from the upper train can reach the lower train only through the pellet (17) in the lower ring. The movement of the lower ring in setting the fuze varies the position of this pellet relative to the upper ring, and determines the length and the time the upper train must burn before the lower train is ignited. Similarly, the lower train must burn around to the point where the body pellet (18) is located, before the flame can be transmitted to the magazine charge. It is apparent, therefore, that a variable length of time train may be set off.

With the fuze set at *safe*, a solid section of the metal in the lower ring completely covers the pellet (18) and, even though the powder trains should become ignited and burn, no flame could be communicated to the magazine charge. Other safety features include the *concussion* plunger (2), which is held away from the firing pin (5) by the split resistance ring (3) until the gun is fired, and the percussion plunger (14), of the Semple type, which is not armed till the projectile leaves the gun.

Time Action.—When the gun is discharged, the concussion plunger (2) moves to the rear, overcoming the resistance of the split ring (3) and carrying the concussion primer (4) against the firing pin. The flame from the sensitive mercury fulminate mixture, augmented by a small igniting charge of black powder, passes out through a vent to the black powder pellet (16) which, in turn, ignites the end of the upper time train.

If the fuze is set at zero, as shown in the left-hand illustration, the flame passes immediately from the beginning of the upper train through the pellet (17) to the end of the lower train, and thence by means of the adjacent pellet (18) directly to the magazine charge. There is thus a direct path from the concussion primer on through to the base charge of the shrapnel, which produces a burst within about 50 ft. of the muzzle of the gun. Such use of shrapnel is termed *canister action.*

If the fuze is set at 21 seconds, the upper time train must burn its full length before the pellet (17) is reached and, similarly, the lower time train must burn its full length before the body pellet (18) is reached. For other time settings, a variable length of time train is interposed between the concussion primer and the magazine charge, the length including that part of the upper train which must burn before the pellet (17) is reached and that part of the lower train which then must burn before the pellet (18) is reached.

The gases from the burning powder trains escape through a vent at the beginning of each train into a circular channel inside each ring, and from there through vents (15) to the air. This is termed interior venting. Some powder-train fuzes have exterior venting, radial holes being drilled through the outside of each ring. Since any variation in pressure affects the rate of combustion of the time train, and hence the

time required for the fuze to function, it is essential that the venting system function efficiently and without material variation within the fuze lot.

Percussion Action.—Action on impact is caused by the percussion plunger (14). When the shrapnel strikes, the plunger with its armed firing pin moves forward against the percussion primer (9). The flame from the primer passes through a channel (10) leading to the magazine charge. The percussion mechanism is designed primarily to insure action of the shrapnel in case of failure, or too long a setting, of the time mechanism. If the fuze is set at *S*, however, it will function only on impact.

Other Powder-train Fuzes.—Certain weapons require the use of fuzes with a longer time of burning than 21 seconds. The necessary increase in time may be attained by using a longer time train, or by use of a blend of black powder with a slower rate of burning, or by a combination of these methods. Also, since the rate of combustion of black powder varies inversely with its density, the rate of burning of a time train can be controlled within certain limits by varying the pressure employed to press the powder in the grooves of the rings.

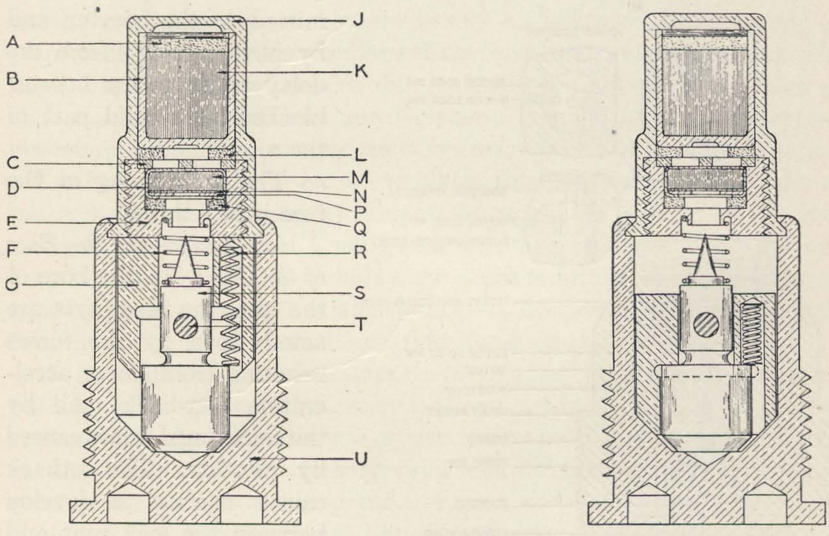
371. Mechanical Time Fuzes.—Time fuzes of the powder-train type are generally satisfactory for field artillery firing but are not completely satisfactory for antiaircraft use. The time of burning is affected by the *air pressure* surrounding the fuze, *temperature, velocity of rotation, composition,* and *density of the black-powder train.* The mechanical time fuze is not appreciably affected by any of these factors and gives considerably better uniformity of burning time at the high angles of antiaircraft trajectories. Several types of mechanical time fuzes have been designed and tested, and a fuze of the *Junghans* type adopted as standard in our service. This fuze contains a clock-work mechanism, driven by two eccentrically weighted gears, actuated by centrifugal force. The force of set-back is used to start the mechanism. An escapement governs the speed of turning of the parts until, at the expiration of the time for which the fuze is set, a firing pin is driven into the primer. Detonator-safety is secured by having the detonator mounted in an eccentrically pivoted disc which keeps it initially out of line with the primer. The escapement mechanism allows the disc to swing slowly outward under the action of centrifugal force until the detonator is brought into line with the primer. Thus the projectile has moved several hundred feet from the muzzle before the fuze is armed, assuring the safety of the gun and its crew.

Another type of mechanical fuze which seems to be equally satisfactory as to functioning is the *Krupp* type. This fuze differs from the

Junghans primarily in the fact that it uses a mainspring rather than centrifugal force for its motive power. It is believed that years of storage in war reserve will have less effect on fuzes of the *Junghans* type since there is no mainspring to be kept under tension as in the *Krupp* type.

372. Base Detonating Fuze, Mark IV.—This fuze (Fig. 330), of the non-delay type, illustrates some of the principles utilized in minor-caliber base detonating fuzes.

Action.—When the gun is fired, the inertia of the plunger (*G*) causes it to move rearward, shearing the pin (*T*), and compressing and locking



Before Arming. After Arming.

Fig. 330.—Minor-caliber Base Detonating Fuze, Mark IV.

the restraining spring (*R*). When it strikes the fuze body, the rear end of the plunger is crimped around the firing pin (*S*). The creep spring (*F*) restrains the firing pin during flight, but on impact the plunger and firing pin move forward together, striking and exploding the primer (*M*). The explosion of the primer is transmitted to the detonator (*K*), which in turn functions the shell bursting charge.

373. Mark X Base Detonating Fuze.—The Mark X Base Detonating Fuze is a delay-action, detonator-safe fuze designed for use in major-caliber, armor-piercing projectiles. It replaces the older types of medium- and major-caliber base detonating fuzes for seacoast guns. The construction of the fuze is illustrated in Fig. 331. The fuze body

contains the booster charge, rotor and its parts, delay pellet, primer, Semple centrifugal plunger, and closing plugs.

The rotor, the axis of rotation of which is not in line with the axis of the fuze, is a disc about 3/8 in. thick. Part of the periphery of the rotor is cut away in such a manner that, at the proper time, centrifugal force will produce rotation of the rotor sufficient to bring the detonator into alignment with the delay pellet and tetryl channel leading to the booster. Detonator-safety is obtained by having the detonator (fulminate of mercury) out of alignment with the tetryl channel so that premature explosion of the detonator cannot be transmitted to the booster, and by having access from the delay pellet to the booster blocked by a solid part of the rotor.

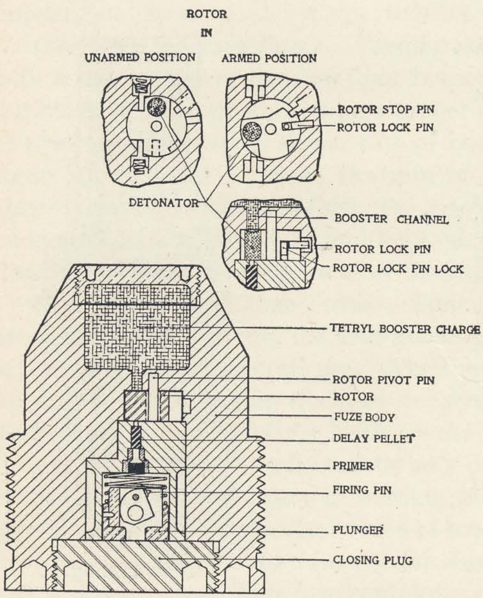


Fig. 331.—Mark X Base Detonating Fuze.

The functioning of the fuze is as follows:

(*a*) *Action in the Bore of the Gun.*—In the bore of the gun, the fuze parts are acted upon by the forces resulting from linear acceleration (set-back) and by the centrifugal forces caused by rotation. The setback causes friction to develop between the lock pins and the fuze body and between the rotor and the fuze body. The frictional forces are greater than the centrifugal forces, and the rotor thus is locked in place in the fuze body. The fuze emerges from the bore of the gun still unarmed, no action having taken place.

(*b*) *Action in Flight.*—When acceleration ceases, centrifugal force causes action. The centrifugal plunger is armed and the two rotor lock pins are thrown out of engagement with the rotor. The rotor rotates into the armed position, with the detonator in line between the delay pellet and the booster channel, as shown in the figure.

The rotor stop pin serves to stop the rotor in the armed position. In the armed position, also, the rotor lock pin (in the rotor) is aligned with a slot cut in the fuze body and is moved by centrifugal force partly

into this slot, thus locking the rotor in the armed position. The rotor lock pin lock moves into position behind the rotor lock pin to hold it in the locked position.

(c) *Action on Impact.*—On impact, the momentum of the plunger carries it forward, overcoming the resistance of the restraining spring. The firing pin is driven into the primer and explodes it. This action ignites the delay pellet, which burns a predetermined time and then explodes the detonator in the rotor. The detonator, in turn, detonates the booster charge, which detonates the main explosive charge of the projectile.

374. Present Tendency in Fuze Design.—The present tendency in point fuze design may be stated briefly as follows: To construct all point fuzes with a single standard shape, size, and weight; to make the fuzes interchangeable between different caliber projectiles; to have all time fuzes, mechanical and powder train, designed for one fuze setter; interchangeability of certain parts between types of fuzes. Practical difficulties may limit the extent to which this policy can be carried out, but it is apparent that many advantages would result from such a fuze system. The number of firing tables would be materially reduced and fire control at the battery would be simplified in firings involving different types of fuzes. The interchangeability feature would be desirable both from the using and the manufacturing standpoints.

375. Adapters and Boosters.—An *adapter* is a metal collar or bushing, with internal and external threads, which "adapts" a fuze to a projectile and permits the use of a certain type of fuze in shell of different kinds and calibers. It is screwed into the nose of the projectile to reduce the size of the opening and to form a seat for the fuze. An opening in the nose of the projectile limited to the size of the threaded portion of a fuze would increase the difficulty of forming and machining the interior cavity of the shell and subsequently increase the difficulty of loading.

The *booster* is the explosive element (usually tetryl) in the explosive train between the detonator and the bursting charge of H. E. Shell. It is sometimes contained in a thin metal *booster casing* screwed to the adapter and extending down into the bursting charge. Figure 332 illustrates an adapter and a booster of this type.

In some of the recent fuzes the booster charge is loaded into and is a part of the fuze. (See Figs. 328 and 331.) This method permits all the more sensitive elements of the explosive train to be shipped and stored with the fuzes, leaving only the insensitive bursting charge to be shipped and stored in the shell.

H. E. Shell are always shipped and stored unfuzed. An *adapter plug*

is screwed into the adapter to keep out dirt and water. In the larger sizes of shell this plug has a ring and is used as a lifting plug in handling.

In chemical shell the booster is called a *burster*, and its function is to burst the shell so that the contents may be released and scattered. It is therefore somewhat greater than the H. E. Shell booster. Chemical

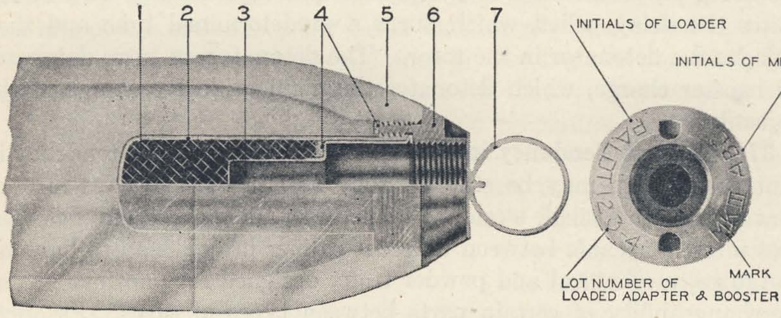


FIG. 332.—Adapter and Booster.

1. Booster charge.
2. Booster casing.
3. Fuze socket.
4. Felt washers.
5. Shell.
6. Adapter.
7. Adapter plug.

shell adapters and bursters are taper-threaded to provide a gas-tight closure.

376. Cartridge Cases.—In our service, cartridge cases are used in cannon up to 105 mm. only, all larger caliber using separate loading ammunition. The cartridge case is made of brass of a size and shape to conform to the powder chamber of the gun. The head of the case is relatively thick and is provided with a flange to allow easy extraction and for seating the round in the gun. In the center of the head is the primer seat, a circular hole into which the primer is seated by pressing to make a gas-tight joint. The primer hole is counter-bored to a slight depth to receive the primer flange. The depth of the counter-bored seat must be exact in order that the primer will be inset the required amount. If the primer is inset too much, a misfire will occur; and, if it is not inset a sufficient amount, it is a source of danger in the event it is struck while handling or loading.

The wall or body of the case is relatively thin and of an outside diameter throughout its length just slightly less than the corresponding diameter of the powder chamber. Figure 309 illustrates a cartridge case as used with an assembled round.

The primary function of the case is to hold the propelling charge. In addition, the pressure of the powder gas expands the thin body of the

case tightly against the walls of the chamber and thereby prevents the escape of gas to the rear. The cartridge case also serves to hold the projectile, permitting the round to be loaded into the gun in one operation.

The cases are drawn from a solid disc of brass in successive passes in hydraulic presses equipped with suitable dies. Army Regulations require that fired cartridge cases be cleaned and returned to the Ordnance Department. They can usually be resized and reloaded for subsequent firing.

377. Service Markings of Artillery Ammunition.—Every round or component of artillery ammunition, and its container, is so marked by painting, stenciling, and stamping as to indicate clearly essential information required for intelligent handling, storage, and use. Projectiles are painted both for ready identification and as a rust deterrent. The body color scheme used to designate types and fillers is as follows: yellow for high explosive; red for low explosive and shrapnel; gray for chemical, with superimposed green, yellow, or red bands to indicate the classification of the chemical agent based upon its tactical employment; blue for practice ammunition, with greatly reduced charge of low explosive; black for drill or other completely inert projectiles.

The stamped or stenciled markings on the projectile include the following: caliber and type of cannon in which used (e.g., 75 G); mark number (model) of shell or shrapnel (e.g., Mk. IV); mean weight of fuzed shell in pounds, or weight symbol; filler used (e.g., TNT, HS Gas, etc.); ammunition lot number (in unfixed or separate loading ammunition only). In fixed ammunition, the cartridge case marking shows the type and lot number of the propellent powder, the muzzle velocity in feet per second, and the ammunition lot number.

The ammunition lot number, together with the ammunition data card accompanying the ammunition, completely identifies every component of the round. The ammunition data card gives tabulated information as to the materials, manufacturer, place and date of loading and assembly, methods used, components, etc.

CHAPTER XVI

BOMBS AND GRENADES

BOMBS

Bombs may be classified according to the filler used as *explosive, chemical,* and *inert.* The standard types employed are designated as *fragmentation, demolition, chemical, practice, drill,* and *gage.* Other types, for which special requirements may exist, include *incendiary, armor-piercing, antisubmarine,* and *antiaircraft.* None of these has been standardized for service use.

378. Fragmentation Bombs.—The destructive effect of this type of bomb is obtained largely through a scattering of fragments of the bomb case and other metal components at high velocity. It is effective against personnel, animals, and light material targets, such as motor transport, airplanes, etc. It is designed primarily for use by attack aviation against ground targets. When equipped with a suitable time fuze, it may be employed by pursuit aviation against bombardment formations, being released at altitudes which will insure safety of the pursuit plane from the machine guns on the bombers.

Complete and uniform fragmentation of the bomb case is desirable, with the pieces of effective size and weight. For use against personnel, a 0.20-oz. fragment with 60 ft.-lb. of energy, sufficient to pass through a $\frac{3}{4}$-in. spruce board, is effective. Against material targets, a 0.30-oz. fragment such as obtained from the 30-lb. bomb is more efficient.

To secure uniform distribution of fragments, and maximum destructive effect against ground targets, the bomb should be detonated in a vertical position above ground. If lying on its side, a considerable part of the fragments will be driven into the earth or projected upwards. However, a bomb released from a plane flying at high speed must be dropped from an altitude of about 4000 to 5000 ft. to attain an angle of impact of about 70°.

When dropping bombs equipped with instantaneous fuzes, the plane should be at an altitude of 800 ft. to insure its safety against flying bomb fragments. Bombing by attack aviation at very low altitudes necessitates the provision of means whereby the vertical and horizontal velocity components of the bomb may be retarded sufficiently during flight to

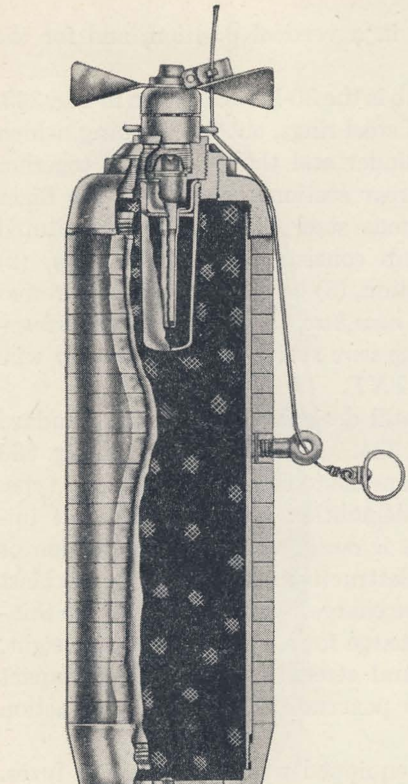


FIG. 333.—30-lb. Fragmentation Bomb, M5.

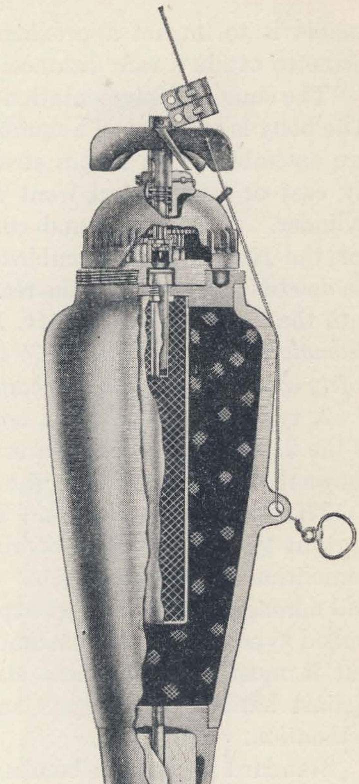


FIG. 334.—25-lb. Fragmentation Bomb, Mk. III.

enable it to impact approximately in a vertical position, and for the plane to attain a safe distance.

The standard fragmentation bomb is the 30-lb. M5 shown in Fig. 333. The body is made up of a number of steel rings, cut from tubing, which are assembled over a thin steel cylinder and the whole held together by cast or forged steel front and rear sections screwed to the inner cylinder. A closely wound continuous steel coil may be substituted for the rings. The assembled bomb consists of (1) *bomb body,* (2) *fin assembly* screwed into the rear section, (3) *booster* and *adapter* screwed into the front section, (4) *Mk. XIV nose fuze,* (5) instantaneous *primer-detonator,* (6) *arming wire,* (7) *arming wire swivel loop,* (8) *arming wire safety clip,* and (9) a 4.5-lb. *charge of TNT.*

A type of fragmentation bomb still designated as limited standard is the 25-lb. Mk. III, shown in Fig. 334. A comparison with Fig. 333 shows the design trend from the stream-line to the cylindrical-body type.

379. Demolition Bombs.—The demolition bomb is the most important type of explosive bomb. It is designed for the destruction or demolition of material targets. Its destructive action is due to the blast and mining effect of the high explosive charge. The bomb is of the thin-walled type to permit a maximum charge for a given aggregate weight, but it must have sufficient structural strength to withstand impact against hard-surface targets and to penetrate intact for delay-action detonation.

Standard demolition bombs are equipped with nose and tail fuzes. Two types of primer-detonators are provided for the nose fuzes, giving instantaneous or short-delay action according to the target and the effect desired. With delayed action functioning, approximately 0.5 cu. yd. of earth is displaced per pound of explosive. The mining action is particularly effective against structural targets. Delayed action functioning produces maximum results against naval targets.

The blast effect from instantaneous action varies roughly as follows, inversely as the square of the distance and directly as the weight of the charge. In tests against a reinforced concrete bridge, a 600-lb. bomb detonated statically 8 ft. from a pillar, shattered it, causing collapse of a span, whereas when detonated at a distance of 12 ft. the blast effect was reduced more than one half and little damage was done to the pillar.

During the War, the bombs manufactured in this country were of streamline shape, both longitudinal and circumferential welds being used. In the immediate post-war development, longitudinal welds were eliminated and the cylindrical shape was introduced in a 2000-lb. bomb.

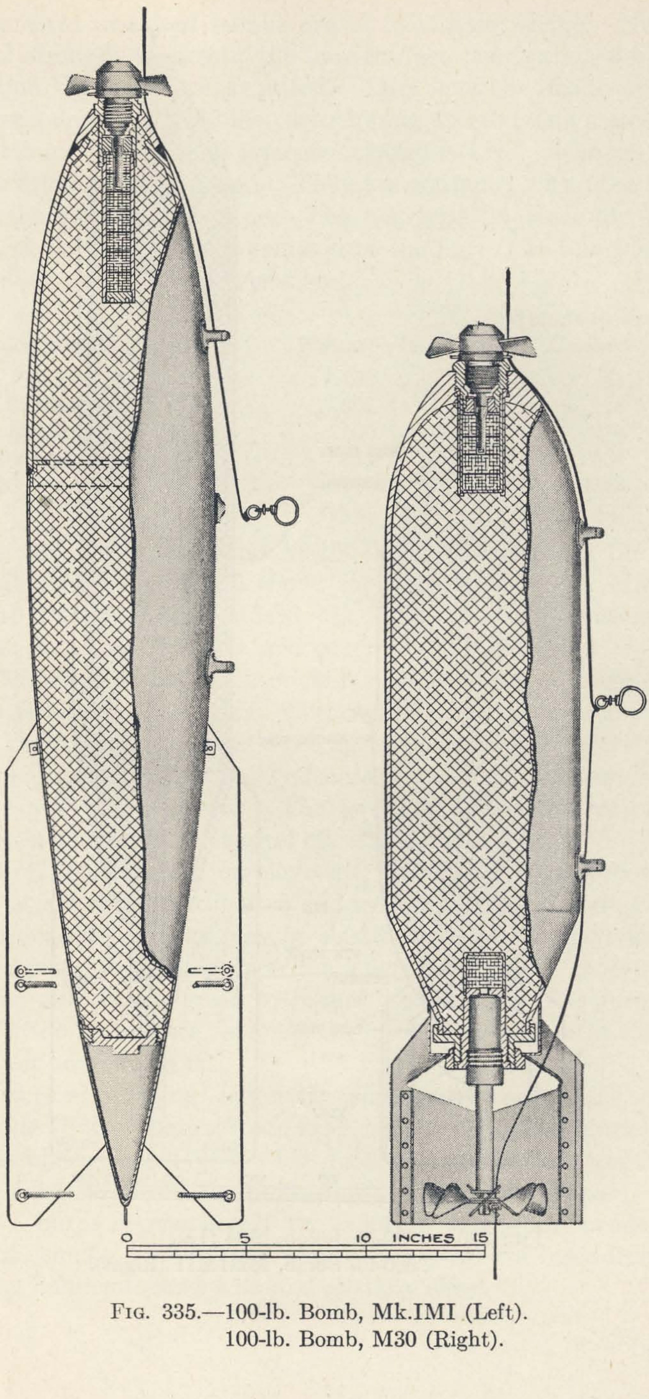


FIG. 335.—100-lb. Bomb, Mk.IMI (Left).
100-lb. Bomb, M30 (Right).

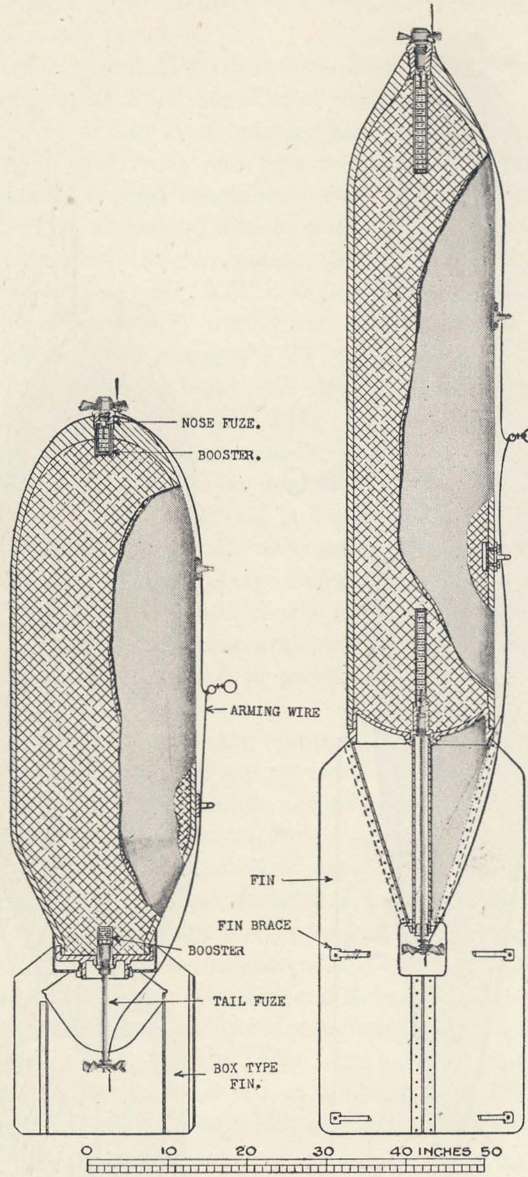


FIG. 336.—2000-lb. Bomb, M34 (Left).
2000-lb. Bomb, Mk.IMII (Right).

The present standard bombs are of cylindrical shape. Necessary structural strength to permit the hard-surface penetration desired for delay-action detonation is required. They may be made either by piercing and drawing steel billet, by cupping and drawing a steel plate, or by welding. The normal explosive charge is TNT, although amatol or other explosive may be used. They are equipped with nose and tail fuzes of the arming-vane type. The box-type fin assembly permits insertion of the fuze without removal of the fin. The following table shows the present standard types:

Bomb Designation	Weight—Lb.	Weight of Explosive Charge—Lb.
100-lb. M30	102	57
300-lb. M31	306	158
500-lb. M43	500	276
1000-lb. M44	971	556
2000-lb. M34	2050	1113

Figure 335 shows the standard 100-lb. M30 bomb and the earlier 100-lb. Mk.IMI. Figure 336 shows the standard 2000-lb. M34 compared with the previous standard Mk.IMII. The illustrations show clearly the shape, components, and general assembly.

380. Chemical Bombs.—Chemical bombs are filled with agents used in war to produce physiological effect, screening smokes, or incendiary action. The term *gas* includes those agents used for their physiological effect, including lung irritants, vesicants, lacrimators, irritant smokes, and nerve and blood poisons. The *screening smokes* and *incendiaries* have some incidental physiological effect.

Based on their tactical employment, the agents employed may be classified as *harassing* (lacrimators and irritant smoke), *casualty*, *screening*, and *incendiary*. They may be classified also as *non-persistent* and *persistent* agents, depending upon the length of time the concentration will remain sufficiently great to require protection. The former are dispersed after 10 minutes, whereas the latter may remain at the point of release for hours or days.

The smoke-producing materials commonly used are titanium tetrachloride (FM), chlorosulfonic acid—sulphur trioxide solution (FS), and white phosphorus (WP). The first two are liquids which react with the moisture of the air, producing a dense white smoke. White phosphorus burns spontaneously on exposure to the air, producing a dense white smoke. White phosphorus is a powerful incendiary, and small flying fragments have a limited casualty effect.

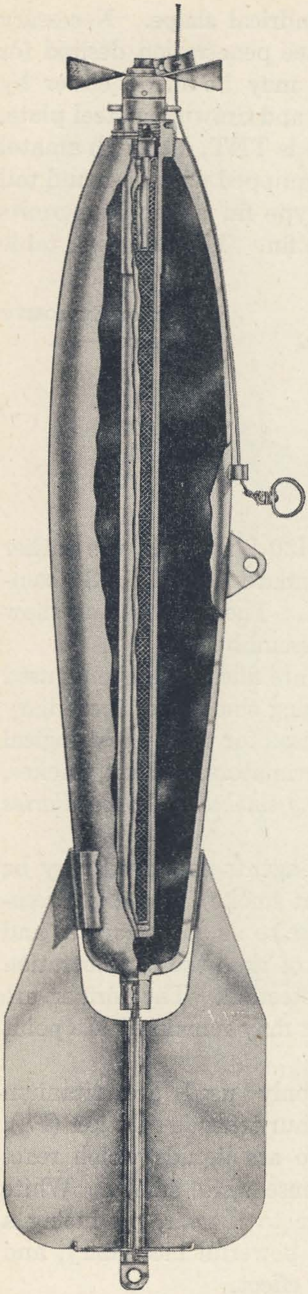


FIG. 337.—30-lb. Chemical Bomb, MI.

Chemical bombs must explode above ground for proper dispersion of the filler; an instantaneous nose fuze is therefore essential. A *burster* of tetryl, extending through the filler, is used to rupture the bomb case and to release or assist in scattering the filler. Since ground penetration is not desired, and since there is no requirement that the bomb body withstand hard-surface impact, thin-walled bodies are employed, permitting the maximum amount of filler.

Small chemical bombs are designed for use by attack aviation. A 100-lb. size may be used by bombardment aviation.

The standard chemical bomb is the 30-lb. MI shown in Fig. 337. It is loaded with either a persistent or a non-persistent chemical. The complete bomb weighs 29 or 33 lb., the filler 9 or 13 lb., and the tetryl burster 86 or 120 grams, when so loaded.

381. Practice Bombs.—The bombs used for practice purposes are obsolete fragmentation and demolition types, or special practice types designed for less expensive manufacture than is possible for standard service bombs. Examples of such less expensive types are: (1) a 100-lb. bomb made from sheet steel about $\frac{1}{32}$ in. thick; (2) a parachute bomb with cast-iron body; (3) a miniature type weighing about $2\frac{1}{2}$ lb.

The spotting charge used to indicate the point of impact may be black powder, a smoke-producing chemical (FS), or a smoke-producing pyrotechnic mixture. A cavity is provided for filling with sand to bring the bomb to standard weight when necessary. With the exception of the 17-lb. Mk.II Bomb, which is arsenal-loaded, all practice bombs are shipped empty, the spotting charge and sand being added just

before they are to be used. To meet any service requirements for dummy bombs, practice types may be dropped empty or inert loaded.

For training in marksmanship, and in manipulation of the safety and arming features of bomb racks, a practice bomb for bombardment aviation should have uniform flight and range characteristics, its trail should be sufficiently small to come within the setting of the bomb sights used on modern airplanes, and it should require arming by the bomb rack when the bomb is released for the spotting charge to function on impact.

382. Drill and Gage Bombs.—Drill and gage bombs consist of standard bomb cases inert-loaded to standard weight, and equipped with standard boosters, fuzes, and primer-detonators, all inert-loaded. Drill bombs are used for training in fuzing operations, handling, and loading on airplanes, and for logistic studies. Gage bombs are used in the testing of new types of airplanes for clearances, capacity, and functioning of bomb racks.

383. Bomb Fuzes.—Fuzes may be classified according to method of arming as *arming-vane* and *arming-pin* types. Based on their location they are termed *nose* and *tail* fuzes. They may also be classed as *percussion* fuzes, which function on impact, with *instantaneous* or *delay* action, and *time* fuzes, which function at the end of the time interval for which set.

All fuzes are so designed that fuzed bombs may be carried safely on aircraft; they arm only on release. The *arming-pin* type arms immediately but the *arming-vane* type must fall a considerable distance and the arming vane make a definite number of revolutions before the fuze is armed. Certain fuzes incorporate a reduction gear as an additional safety element, a large number of turns of the vane being necessary to unscrew the arming mechanism one turn.

The fuze is connected with the arming mechanism of the bomb rack by means of an *arming wire*, which may be released to fall with the bomb, or one end may be held in the bomb rack. If released, the bomb will be dropped *safe;* the fuze is prevented from arming, and will not function on impact; if one end is held in the rack, however, the arming wire will be jerked from its connection with the fuze by the weight of the falling bomb, and the fuze is then armed or permitted to arm.

The *primer-detonator* assembly, consisting of a sensitive percussion type *primer*, a *delay element* if one is required, and a *detonator*, may be an integral part of the fuze or a separate assembly to be screwed on or assembled to the fuze body. The two types of primer-detonators give instantaneous or 0.1-second delay action according to the way they are loaded. The delay action is accomplished by a compressed black powder pellet placed between the primer and the detonator. The

detonator extends directly into the *booster* in explosive bombs, and into the *burster* in chemical bombs. Both mercury fulminate-tetryl and lead azide-tetryl detonators are employed.

The fuze may be screwed directly into the bomb body or it may be screwed into an *adapter-booster* as illustrated in Fig. 333. The *adapter* element is a bushing which is received by either the nose or the tail threads of the bomb body, and which in turn receives the fuze. The *booster charge*, of tetryl and TNT, or tetryl only, extends well into the main explosive charge so as to obtain complete high-order detonation.

Figure 338 shows the Mk.VIIMII Nose Fuze for demolition bombs. It is of the arming-vane type and has a mechanical firing mechanism

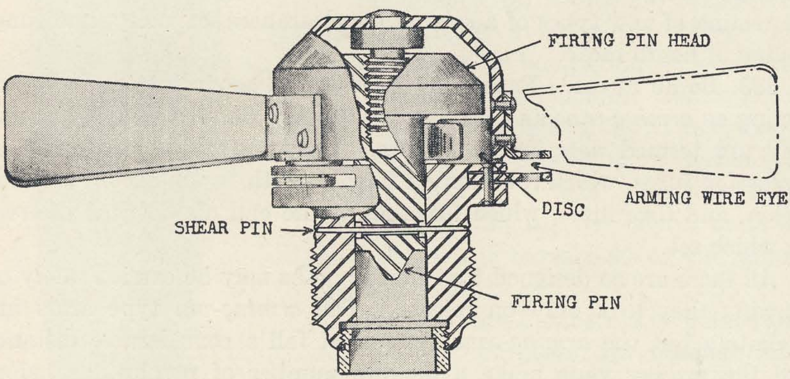


FIG. 338.—Mk.VIIMII Nose Fuze.

only, with no explosive elements. The vane is held from turning by the arming wire which runs through an eye in the fuze body and a corresponding eye in the vane. If the arming wire is dropped with the bomb, the fuze cannot arm. When, however, one end is held in the bomb rack, the other end will be jerked from the eye of the vane as the bomb is released. The vane is then free to turn under the action of air pressure and will spin off after about 18 turns, at which time the bomb will have dropped a safe distance. The seven segmental discs under the head of the firing pin are then free to fall out, leaving the firing pin restrained only by a 0.064-in. shear pin of soft brass. On impact, the firing pin moves to the rear, breaking the shear pin and striking the primer, thereby causing the successive functioning of the explosive train consisting of the primer, delay element if any, detonator, booster, and charge.

Figure 339 illustrates the Mk.VMI Tail Fuze for demolition bombs.

It is of the arming-vane type, with mechanical firing mechanism and no explosive element. When the bomb is released, and the arming wire

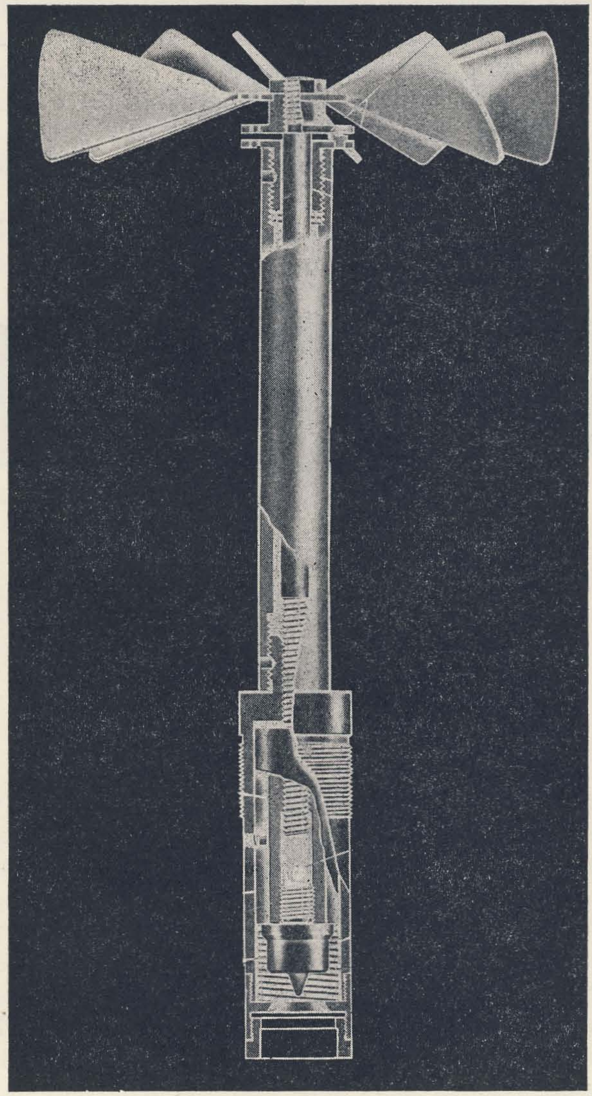


FIG. 339.—Tail Fuze Mk.VMI.

retained in the bomb rack, the vane is free to spin. After about 20 turns, the vane and the long arming vane stem are unscrewed from the

firing-pin weight, the part which includes the firing pin. The vane and its stem continue to rotate until entirely unscrewed from the fuze assembly, when they fall away. The firing-pin weight is now supported only by a light spring which holds the firing pin away from the primer. Upon impact, the retardation of the bomb causes the weight to move forward, compressing the spring and forcing the firing pin into the primer, thereby causing the successive functioning of the elements comprising the explosive train. Until such time as this fuze is assembled to the bomb, the firing-pin weight is positively held by a lock pin as shown in Fig. 341.

The Mk.XIV Nose Fuze for fragmentation and small chemical bombs is shown in Fig. 340. Its operation is similar to that of the Mk.

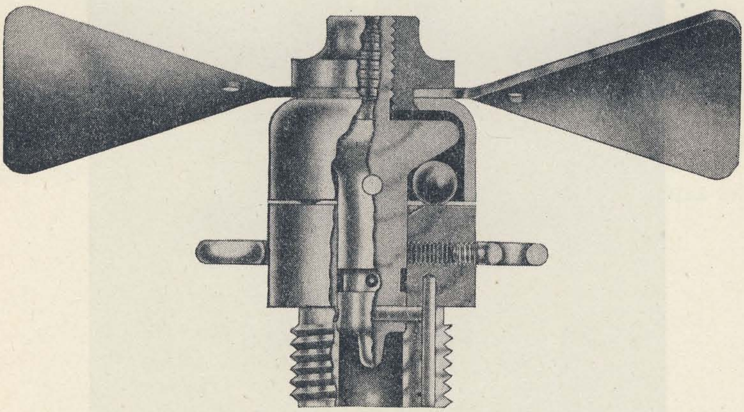


FIG. 340.—Nose Fuze Mk.XIV.

VIIMII Fuze. When the bomb is released and the arming wire withdrawn, the vane drops off after about 10 turns. The balls supporting the firing-pin head also fall out, leaving the firing pin supported only by a 0.032-in. shear pin of annealed magnet wire. Upon impact, the firing pin moves to the rear, breaking the shear pin and striking the primer.

A different type of fuze is used in the tail of the standard demolition bombs. The M100 Fuze, used in the 100-lb. and 300-lb. bombs, is illustrated in Fig. 341 and is also shown in Fig. 335. The M101 Fuze, used with the 600-lb. bomb, and the M102 Fuze, designed for the 1100-lb. and 2000-lb. bombs, (see Fig. 336), differ from the M100 only in respect to length. The increased length was necessary to assure proper spinning of the arming vane. In this type of fuze, the primer, delay element, and detonator are made part of the fuze assembly, eliminating the necessity for a separate primer-detonator and making the fuzing opera-

tion safer and simpler. The functioning of this fuze is similar to that of the Mk.VMI Fuze previously described. A simple reduction gear has been incorporated in the latest design of M100, M101, and M102 fuzes, the mechanism requiring 30 turns of the arming vane for each

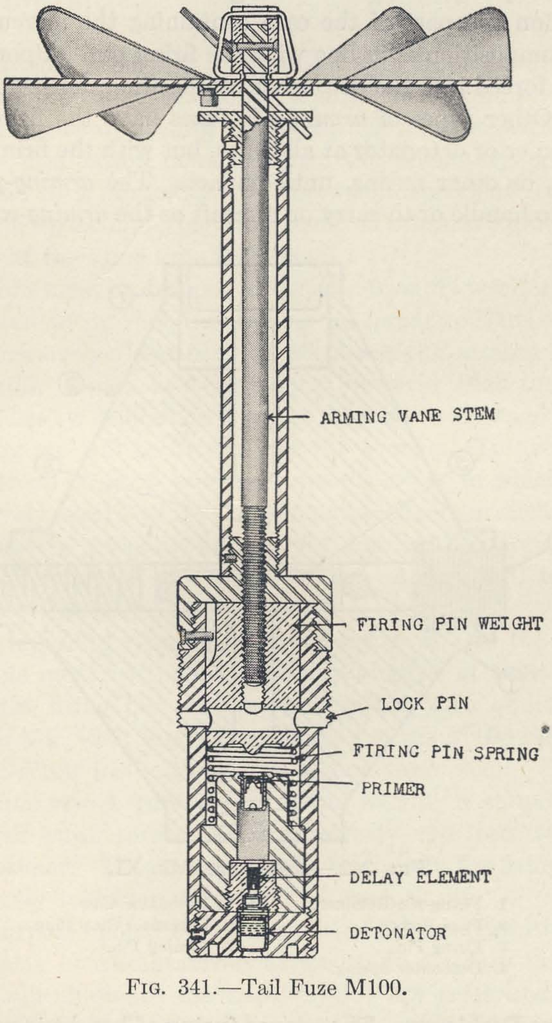


FIG. 341.—Tail Fuze M100.

revolution of the arming-vane stem, and a total of 550 turns of the vane to complete the arming. The fuze illustrated in Fig. 341 is an older type, not modified to incorporate the delayed-arming mechanism.

Figure 342 illustrates one type of *arming-pin* fuze. In the bombing rack, the *arming wire* passes through a projecting end of the *arming pin,*

preventing arming. An inert part of the *detonator case* is then in line with the *firing pin.* As the bomb is released, the arming wire is withdrawn, and the arming pin is expelled through the action of the *arming-pin spring.* The detonator is now free to slide, under the action of the *detonator spring,* until it bears against the *detonator stop plug,* in which position the part of the case containing the mercury fulminate detonator composition is in line with the firing pin. Upon impact, the firing pin is forced into the detonator composition, initiating the explosive train. Other types of *arming-pin* fuzes have the firing pin in line with the primer or detonator at all times, but with the firing pin held by a shear pin, or other means, until impact. The *arming-pin* fuzes are not as safe to handle or to carry on aircraft as the *arming-vane* type.

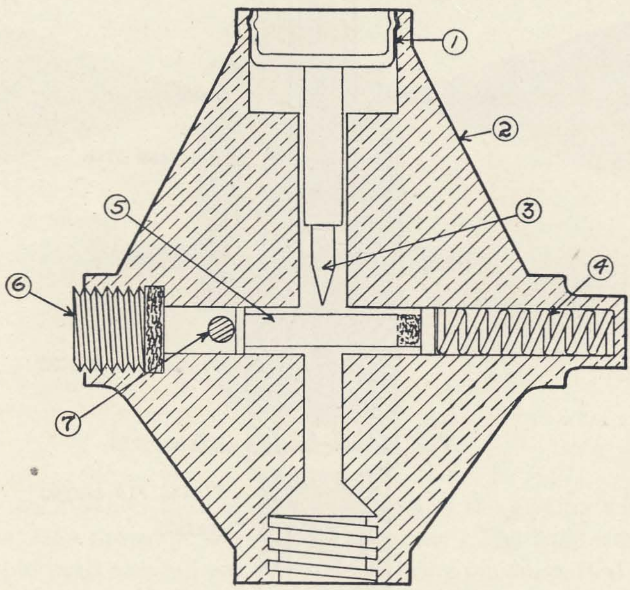


FIG. 342.—Nose Fuze, Mk. XI.

1. Firing-pin Retainer.
2. Fuze Body.
3. Firing Pin.
4. Detonator Spring.
5. Detonator Case.
6. Detonator Stop Plug.
7. Arming Pin.

384. Fuze Problems.—The proper fuzing of bombs is nearly as complicated as that of artillery projectiles. The principal problems are to secure or obtain

1. Positive action.
2. Non-functioning if dropped *safe.*

3. Safety in handling and assembling in bombs.
4. Selective delay and non-delay action where required.
5. Interchangeability as between bombs of the same general type.
6. Delayed arming.

Positive action is insured in standard demolition bombs by use of both nose and tail fuzes. Although a single fuze is quite reliable, the hazard and expense of getting a bombardment plane with its load of bombs to its destination demands that the possibility of bomb failure be reduced to a minimum. With two independent fuzes, each of which may fail, for example, once in a hundred times, the probability that both will fail at the same time is 1/10000.

As all bombs must be dropped at times in friendly territory, a positive *safety* is desired to prevent functioning on impact. This safety is obtained, as previously described, by releasing the arming wire to fall with the bomb. There is a possibility however that the nose fuze, especially in heavy demolition bombs, may be so damaged on impact that the firing pin will be driven into the primer. To avoid this possibility, the trend of development is towards a fuze in which the detonator is positively separated from the bursting charge in such a way that, unless the fuze be properly armed, the accidental functioning of the detonator cannot set off the main charge. A standard fuze now incorporates this feature.

Safety in handling is provided in various ways. In the *arming-vane* type, the vane must be turned a definite number of times to unscrew it and free the firing pin or firing-pin weight. An additional safety feature of the Mk. VMI Fuze, Fig. 339, and of the M100 Fuze, Fig. 341, is the double-screw fastening of the arming-vane stem. Even though the stem is unscrewed from the firing-pin weight, it cannot be pushed past the upper screw thread in the fuze body and force the firing pin against the primer. Before assembly in the bomb, the firing-pin weight is also positively held from the primer by the lock pin.

An "all-purpose" nose fuze for demolition bombs, permitting selective setting for delay or instantaneous action, as in artillery fuzes, is desirable. This will eliminate the necessity for the issue and use of two types of primer-detonators, and for their assembly to the fuzes in the field. Delay action only is used in tail fuzes as their sole function is to insure certainty of action in case of failure of the nose fuze.

Complete interchangeability of fuzes as between various types of bombs is not feasible. The nose and tail fuzes of demolition bombs are not mutually interchangeable. It is highly desirable, however, that

these two fuzes be so designed that they can be interchanged with corresponding nose and tail fuzes on any type of demolition bomb.

The time required for the arming of an arming-vane type fuze is, of course, dependent on the air speed at which the bomb is released. With the introduction of high-speed planes it is evident that the time required for arming has been considerably reduced. In order to assure safety to the airplane on take-off and release of bomb, it was considered advisable to increase the time required for the fuze to arm. This, in fuzes for demolition bombs, is being accomplished by means of a simple gearing arrangement. In the fuze for fragmentation bombs used by low-flying attack airplanes, the delayed arming is accomplished by means of a powder-train delay element. It is not practicable to use an arming vane on such a fuze, because the speed of the bomb is reduced to such extent by the parachute soon after release that the air stream past the vanes will not be of sufficient intensity to assure their satisfactory operation.

385. Bomb Testing.—Bomb testing is an important proving-ground activity. All types of bombs are subjected to *functioning*, *trajectory*, and *safety tests*. Other tests depend upon the particular type of bomb; they include *hard-surface* and *high-panel* tests of demolition bombs, and *pit*, *matériel*, *low panel*, and *silhouette* tests of fragmentation bombs.

The functioning test determines the suitability and efficiency of the suspension arrangement, fuzing, explosive train, and loading. The sensitivity and action of fuzes and primer-detonators are observed, and the craters made by the bombs are measured.

The trajectory test is concerned with determination of the *ballistic* characteristics of each type of bomb. The test may be omitted from bombs designed to be dropped from such low altitudes that bomb sights are not used. For demolition and antiaircraft fragmentation bombs, it is essential that accurate ballistic data be available.

The *safety test* is to determine whether the bomb can be dropped *safe*, that is, without detonation at impact. It is concerned with the sensitivity, strength, and general design of the fuze, the sensitivity and suitability of the bomb filler, and the structural strength of the bomb assembly.

The *hard-surface test* has been standardized for testing the strength of demolition bomb cases. The surface on which dropped consists of a block of concrete 1 ft. thick, placed over crushed rock 2 ft. thick. The bombs (except the 100-lb. size) must penetrate the concrete without breaking or becoming unduly deformed when the maximum diameter of the bomb has passed through the concrete. The altitude of drop varies from about 1500 to 4000 ft., the greater altitude being used for

the smaller bombs. Although the 100-lb. bomb is tested on the hard surface, it is not required to pass such a rigid test, inasmuch as use against highly resistant targets is not contemplated.

The *high-panel test* is to determine the magnitude of blast and the destructive effect of fragments of the bomb. The bomb is placed nose down on a heavy piece of armor plate and detonated statically. The blast effect is measured by simple blast meters placed at intervals of 50 ft. from the bomb. These are simply sheets of tested paper clamped between boards, through which varying sizes of holes have been bored. The relative blast effect of the bomb tested is determined by the smallest hole blown through at the various distances. The destructive effect of the bomb fragments is determined by the use of 2-in. oak planks at distances of 75 and 150 ft. After detonation, the holes are counted and photographed.

The *pit test* is to determine the extent and character of fragmentation. The fragmentation bomb is detonated statically in a sand pit, the fragments recovered by screening through screens of different mesh, and their number and size ascertained.

The *matériel test* is a static test of fragmentation bombs, to determine their effectiveness against material targets such as trucks, airplanes, etc.

The *low-panel test* is designed to determine the comparative casualty effect of fragmentation bombs when detonated statically. The panels, each representing approximately the area of a man in the standing position, are about 6 ft. high, 13 in. wide, of 3/4-in. spruce, arranged concentrically around the bomb at distances of 10, 20, 30, 40 and 50 meters. The effectiveness of a bomb is determined by the number of panels perforated and the number of perforations, at the various distances.

The *silhouette test* is to determine the casualty effectiveness of the fragmentation bomb dropped from the airplane and detonated on impact. Record is made of the size and character of the crater, the number of panels perforated, and the number of perforations.

386. Bomb Design.—Many important changes have been made in bomb design, due largely to new methods of manufacture. The first streamline demolition bombs were made by welding sheet metal sections longitudinally, and then attaching these sections and nose castings, if any, by means of circumferential welds. This method was not satisfactory as the bomb tended to rupture on hard-surface impact at the welded seams, especially the longitudinal welds.

As a step to improved performance, the longitudinal seams were eliminated and only circumferential welds used. In the cylindrical

2000-lb. Mk.I and Mk.IMI Demolition Bombs, nose and tail steel castings were used; their attachment to the cylindrical body has been previously described. These withstood the hard-surface test satisfactorily, but it was evident that their ability to resist rupture was the result of careful hand-welding operations, the attainment of which in an emergency is doubtful.

The next step was to eliminate welding entirely. The 2000-lb. Mk. IMII Bomb was the first of such design. This is characteristic of the present standard demolition bombs which are made by either (1) the pierced-billet method or (2) the cupped-plate method of drawing seamless steel tubing, as in the manufacture of oxygen cylinders. It may also be possible to manufacture the small standard demolition bombs by upsetting one end of a seamless tube and then swaging both ends to the desired contour, the upsetting operation being necessary to obtain the desired nose thickness. Present indications, based on actual procurement, are that the bombs made by either the pierced-billet or cupped-plate methods will cost no more than welded bombs, when purchased in reasonable quantities However, in order to provide increased facilities for the manufacture of demolition bombs in time of emergency, modern processes of welding have been and are being investigated.

As far as stability in flight of cylindrical demolition bombs is concerned, all tests thus far conducted indicate that the flight characteristics are excellent. Tests conducted at the Proving Ground and in the wind tunnel at the Bureau of Standards indicate that the resistance encountered in flight by well-designed cylindrical bombs is no greater than that of the streamline type. This is due to the comparatively low velocities of bombs, and to the fact that we cannot deal with a true streamline body, but with one having a nose fuze, suspension lugs, fin assembly, etc., which disturb the air flow to a large extent. Because of these appendages, the advantage of the streamline form is largely lost.

Figure 343 shows the operations in the manufacture of the one-piece 600-lb. M32 Demolition Bomb by the pierced-billet method, as carried out by one of the leading manufacturers. In this process, a billet 11 in. $\times$ 11 in. $\times$ $15\frac{1}{2}$ in., weighing approximately 516 lb., and free from seams and flaws, is first brought up to a forging temperature of approximately 2300° F. After removal from the furnace, all loose scale is removed and the billet is placed in a vertical 1500-ton hydraulic press, where it is upset and cupped in two operations, to the contour indicated in the figure as "1st Forging." The upset and cupped forging is then reheated in a furnace to 2300° F., placed in a horizontal 250-ton hydraulic press,

and drawn through 4 dies in one operation. The cylindrical body and nose end are then rough-machined and the open end cut off. Following this operation the forging is again heated to 2300° F., placed in a horizontal 250-ton hydraulic press, and drawn to the finished diameter through 2 dies in one operation. The nose end of the bomb is then machined to the finished contour, and the open end cut off for the "close-in" operation. The latter is accomplished by two operations in a 500-ton hydraulic press after the open end has been reheated. In the final operation, the neck of the open end is machined to the desired length and contour, and both ends are threaded to receive the fuzes.

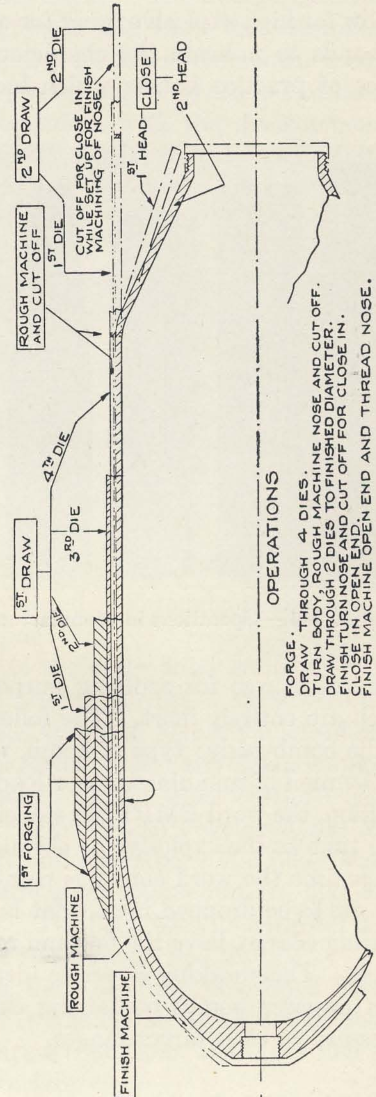


Fig. 343.—Operations in Manufacture of 600-lb. Bomb, M32.

Aluminum alloys have been considered as a means of reducing the weight of demolition bombs. Tests conducted over the hard surface have indicated that bombs made from such alloy, having a tensile strength and elongation comparing favorably with those of the steel used in fabricating bombs, will shatter on impact.

Figure 344 shows the operations in the manufacture of the 30-lb. chemical bomb body, by first spinning one end closed and then swaging to final shape. The spinning operation is accomplished by placing the piece in the chuck of a spinning machine, after the end to be closed has been heated. The friction set up by the tool then raises the heat of the free end to a welding temperature and closes it completely, as shown in the third figure from the left. The next four views show typical swaging operations.

387. Painting and Marking for Identification.—Every round or component of ammunition and the packing containers are so marked by painting, stenciling, or stamping that proper identification is assured. The body color scheme to differentiate types of bombs is as follows: yellow for high explosive; gray for chemical bombs, with circular stripes or bands to indicate the character of the chemical filler; blue for all types of practice bombs which have or are to have an explosive or

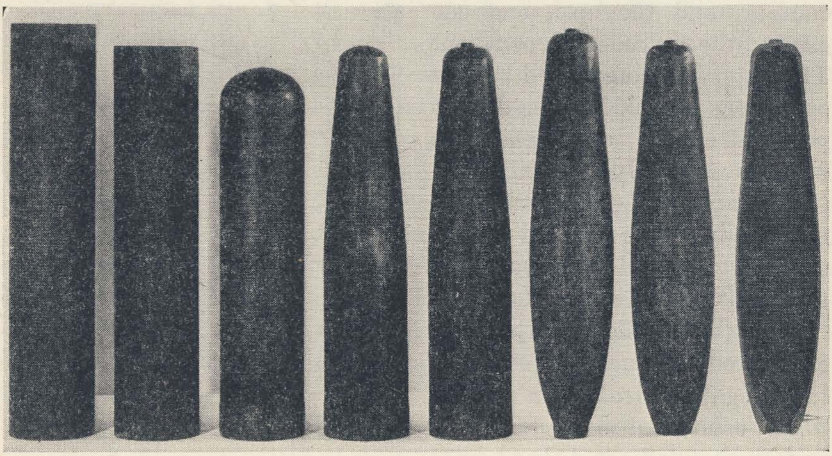


Fig. 344.—Operations in Manufacture of 30-lb. MI Chemical Bomb Body.

chemical charge for spotting purposes; black for drill or gage bombs which are entirely inert. The following data are stenciled or stamped on the bomb body: type of bomb, weight and model, filler, lot number, and symbol of manufacturer or loading plant, and date of loading. In addition, the word EMPTY is stenciled in white on practice bombs until such time as the explosive or chemical charge is placed in the bomb, at which time the word empty is painted out with blue. Practice bombs that are to be dropped inert, that is, without any explosive or chemical spotting charge, have the fins and rear body portion painted black prior to use. This marking serves to identify them, and to distinguish them from practice bombs containing explosive elements, when it becomes necessary to clear target ranges.

GRENADES

The use of the grenade as a weapon dates from the discovery of explosives. The hand grenade is in no sense a new device; history records its use as early as the fifteenth century. The first grenades were somewhat of the shape of a pomegranate and from this resemblance the name originated. By the middle of the seventeenth century, employed by selected soldiers called *grenadiers*, the grenade had become an important military weapon. Coincident with the development of cannon and small arms of greater power, range, and accuracy, the use thereafter declined and, by the middle of the eighteenth century, the grenadier had almost disappeared from the battlefield and the grenade was practically obsolete.

The special conditions existing at Port Arthur in the Russo-Japanese war led to their revival. A variety of types of crude design were improvised and used effectively by both armies. There followed a limited development of both hand and rifle grenades, and more or less spasmodic use, by other armies.

In the early part of the World War, the stabilization of the western front and the resort to trench warfare demonstrated anew the value of the grenade for close fighting. The German army had an initial advantage through possession of an acceptable type that could be placed in immediate production. The Allies were forced to improvise until the several required types could be developed. Throughout the war the grenade remained an important weapon.

388. World War Types.—Many of the early hand grenades of this period had long handles and special arming devices. They were awkward to carry, difficult to use in the trenches, and gave considerable trouble on account of premature explosions. The early types employed percussion fuzes, exploding on impact. Safety considerations led to the general adoption of time fuzes. The British developed the Mills type of grenade which was both safe and effective. The body was of cast iron, grooved externally to insure good fragmentation, and filled with a high explosive such as amatol. The fuze, with its 5-second delay element, was ignited mechanically as the grenade was thrown.

When the United States entered the war, fully developed French and British designs were available. It was merely necessary to select, and to adapt to American manufacturing conditions, the types that had proved most satisfactory in trench warfare.

389. Present Types of Hand Grenades.—Since the war there has been considerable development and standardization of this matériel. Certain types have been eliminated and others added. The standard grenades, with the fuzes and charges used, are as follows:

Type	Designation	Fuze	Filler
Fragmentation	Mk.II	M10	E. C. Blank powder
Gas-irritant (CN - DM)	M6	M200	Chloracetophenone Diphenylaminechlorarsine
Gas-irritant (CN)	M7	M200	Chloracetophenone
Smoke (HC)	M8	M200	Smoke-producing mixture
Practice	Mk.II	M10	Black powder
Dummy	Mk.I	None	None

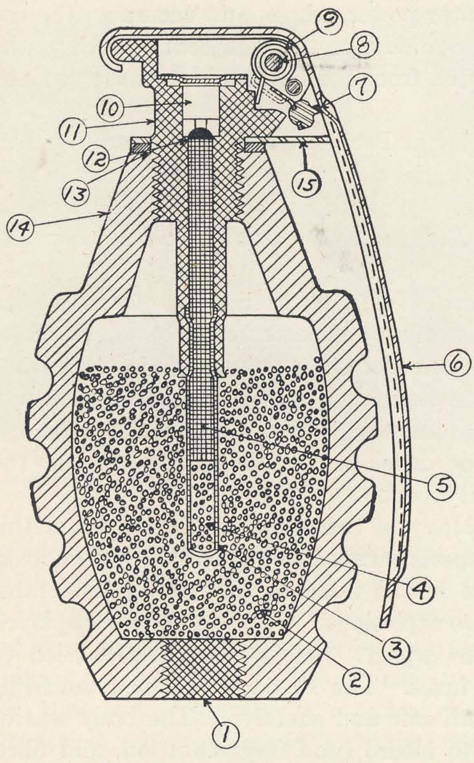


FIG. 345.—Mk.II Fragmentation Grenade.

1. Filling Hole Screw.
2. Bursting Charge.
3. Case.
4. Igniting Charge.
5. Time Fuse.
6. Lever.
7. Striker Point.
8. Hinge Pin.
9. Spring.
10. Primer.
11. Fuze Body.
12. Priming Cap.
13. Washer.
14. Grenade Body.
15. Fuze Sealer.

390. Fragmentation Grenades.—The standard Mk.II fragmentation Hand Grenade with M10 Fuze, is shown in Fig. 345. The body is of cast iron, grooved circumferentially and longitudinally to insure effective fragmentation. The bottom is closed by a die-cast screw and the top threaded to receive the fuze.

The firing mechanism of the fuze consists of a steel striker horizontally hinged in a recess between the two wings of the fuze body, actuated by a steel coiled spring. The striker is held in position, against the tension of the spring, by a lever, one end of which hooks under the protruding lip of the fuze body and the other extends downward along the grenade body. A cotter pin, with a ring attached, extends through and secures the lever to the fuze body, constituting a safety device. The fuze assembly includes an explosive train consisting of a mercury fulminate percussion primer, a 2-in. length of commercial fuse, and an igniting charge of black powder, the whole protected against moisture, dirt, or other foreign material.

The lever is held in position against the grenade body as the safety pin is pulled out and the grenade thrown. When the grenade leaves the hand of the thrower, the firing pin, through the action of the spring, throws off the lever and flies against the primer, exploding the priming charge. The primer ignites the fuse which burns for 5 seconds and then sets off the igniting charge. The igniting charge in turn sets off the bursting charge of E. C. powder, rupturing the grenade body.

During the war, fragmentation grenades were filled with either TNT, amatol, or a nitro-starch explosive. The charge of 0.74 lb. of E. C. powder gives more uniform fragmentation. About 40 fragments result, with an effective dispersion radius of approximately 30 yd., although small fragments may fly a distance of 200 yd. It is essential, therefore, that the grenade always be thrown from cover. The use of the E. C. filler eliminates the use of detonating fuzes and also permits shipment and storage of the assembled grenade and fuze. With a high-explosive filler, the explosion of one grenade may cause mass detonation of the others in the packing box, whereas no sympathetic explosion results when the E. C. powder is used.

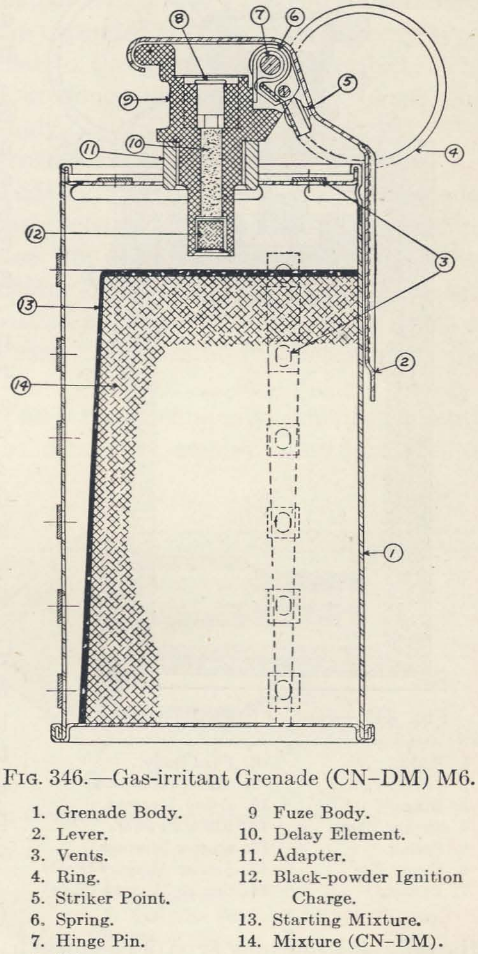


FIG. 346.—Gas-irritant Grenade (CN–DM) M6.

1. Grenade Body.
2. Lever.
3. Vents.
4. Ring.
5. Striker Point.
6. Spring.
7. Hinge Pin.
8. Primer.
9. Fuze Body.
10. Delay Element.
11. Adapter.
12. Black-powder Ignition Charge.
13. Starting Mixture.
14. Mixture (CN–DM).

391. Chemical Grenades.—The chemical grenades are filled with various appropriate chemical agents which are dispersed by ignition or through the action of a burster. They are used in the peace-time training of troops in simulated gas and smoke situations, and certain types are extremely effective in the quelling of riots and other civil disturbances.

The Grenade, Hand, Irritant (CN–DM), M-6, shown in Fig. 346, is of the fast-burning type. The chemical filler is a 10-oz. mixture of chloracetophenone (CN, lacrimatory), diphenylaminechlorarsine (DM, irritant), smokeless powder, and magnesium oxide. It is covered by a starting mixture of meal powder held in a binder of celluloid and acetone, poured over the compressed filler.

The M200 igniting fuze is similar in operation to the fuze used in the fragmentation grenade, except that the explosive train is shorter and the delay element is of pressed powder giving a 2-second delay.

The cylinder case is of tin plate, containing 3 longitudinal rows of 6 holes each in the body, and 6 holes in the top, covered with zinc-oxide adhesive tape. The vapor from the fast-burning filler issues from these holes. It has an immediate lacrimatory and nauseating effect on unprotected personnel.

The Grenade, Hand, Lacrimatory, M7, is also of the fast-burning type. It is similar in construction and operation to the M6 irritant grenade, but the chemical filler is chloracetophenone (CN), smokeless powder, and magnesium oxide.

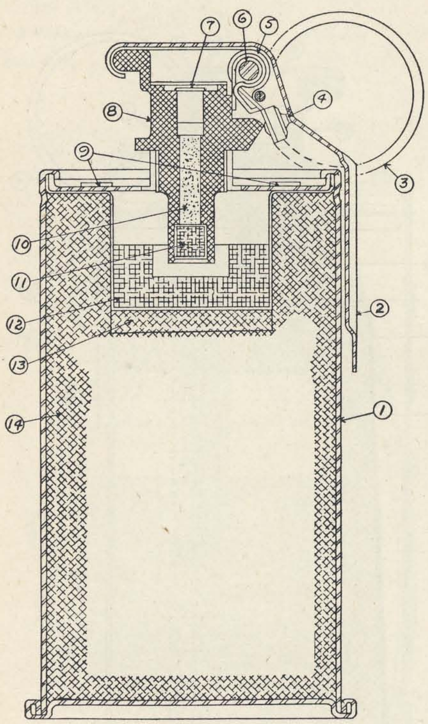


FIG. 347.—Smoke Grenade (HC), M8.

1. Body.
2. Lever.
3. Ring.
4. Striker Point.
5. Spring.
6 Hinge Pin.
7. Primer.
8. Fuze Body.
9. Adhesive Tape.
10. Delay Element.
11. Black Powder.
12. Starter Mixture.
13. Starter Mixture (Fast)
14. Smoke Mixture (Slow)

The Grenade, Hand, Smoke, (HC), M8, shown in Fig. 347, is the only slow-burning type of chemical hand grenade now standard. The case is similar to that described for the irritant grenade except that only 4 holes are provided in the top and none in the body. The smoke mixture of hexachlorethane, powdered zinc, and zinc oxide fills the entire case except for a small void at the top for the fuze and starting mixture. The smoke consists primarily of very small particles of zinc chloride which readily absorb moisture from the air and become highly obscur-

ing. The grenade burns at full volume for about 3 minutes. The smoke has no physiological effect. At present this grenade is authorized for use only by the Air Corps, as an emergency signal. Other training requirements for smoke grenades are met by use of smoke candles or smoke pots.

The Grenade, Hand, Lacrimatory (CN), Mk. V is no longer standard, but will be used until stocks are expended. It is a slow-burning type. In general operation it is similar to the grenade just described. The case, however, is of sheet steel, of the conventional grenade shape, and the filler is chloracetophenone only.

White phosphorus hand grenades are now obsolete.

392. Practice Hand Grenades.—The Practice Hand Grenade, Mk. II, is similar in general appearance and functioning to the standard fragmentation grenade and uses the same igniting fuze. The filler, however, is a small 22-gram charge of black powder formed into two pellets, inserted through the bottom opening of the fuze body which is then closed with a commercial cork. There is no fragmentation of the grenade body.

393. Dummy Hand Grenades.—For preliminary practice, dummy grenades are used. They are solid castings, employing no fuze or filler

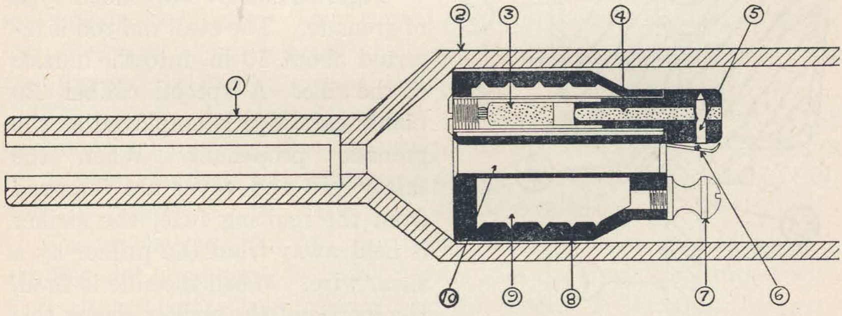


FIG. 348.—Rifle Grenade and Discharger.

1. Discharger Sleeve.
2. Discharger Body.
3. Detonator.
4. Time Fuse.
5. Primer.
6. Striker Point.
7. Plug.
8. Grenade Body.
9. Explosive Filler.
10. Bullet Way.

of any kind. The casting is of the same general shape as the fragmentation grenade, the fuze and lever being simulated by cast projections.

394. Rifle Grenades.—Rifle grenades are designed to secure increased range beyond the limits of hand throwing. Two types were developed during the war, one of which was hurled from a special discharger fitted to the muzzle of the service rifle, the regular ball ammuni-

tion being used, and the other of the so-called rod type, which required the use of special blank cartridges.

Figure 348 shows a cross section of the V. B. rifle grenade as it rests in the discharger. As the bullet passes out of the barrel and through the bullet way of the grenade, it forces the striker against the primer, thus igniting the fuse. The powder gas emerging from the muzzle expands under the grenade, forcing it from the discharger. The fuse burns for 8 seconds and then sets off the detonator which, in turn, sets off the high-explosive charge. The maximum range attainable is slightly over 200 yd. The effectiveness of the grenade is based upon fragmentation action.

Figure 349 shows a rodded type of grenade. The steel tail rod is inserted about 10 in. into the muzzle of the rifle. A special caliber .30 blank cartridge is employed as the grenade propellant. When the safety pin and cover are removed from the igniting fuze, the striker is held away from the primer by a shear wire. When the rifle is fired, the inertia of the striker shears this wire and sets off the primer. A delay fuse, burning about 8 seconds, is employed. The grenade shown is the Smoke Rifle Grenade, Mk I, no longer standard.

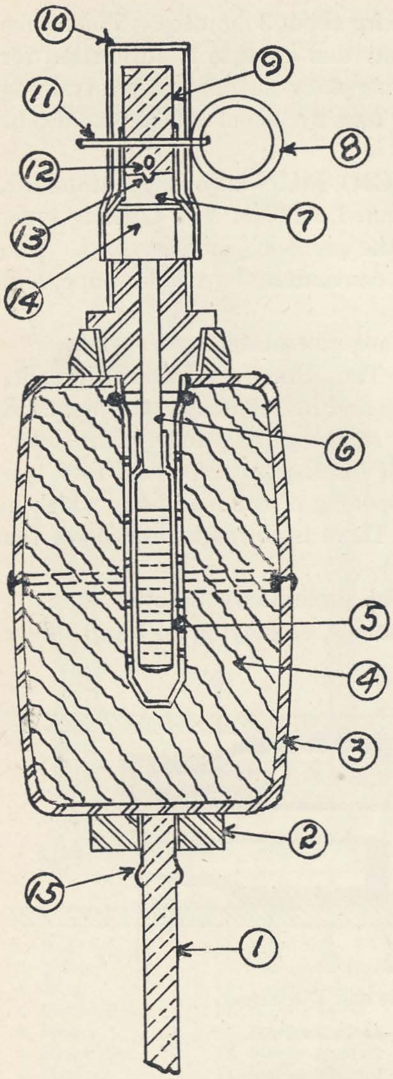


FIG. 349.—Rod Rifle Grenade.

1. Rifle Rod.
2. Base Disc.
3. Body.
4. Filler.
5. Detonator.
6. Time Fuse.
7. Striker Chamber.
8. Ring.
9. Striker.
10. Cover.
11. Safety Pin.
12. Shear Wire Hole.
13. Striker Point.
14. Primer.
15. Rod Projections.

The rifle is not suited to the discharge of grenades; it is subjected to strains for which it was not designed. Attempts have been made to design a discharger containing a firing mechanism, which could be attached to the butt of

the rifle for use. This also puts a severe strain on the rifle and is undesirable. It is probable that the solution will be to design a discharger which will not be used in connection with the rifle, but will form a separate item of equipment.

No rifle grenade is now standard. The service desires a combination hand and rifle grenade but no satisfactory design has been evolved, nor is it probable that the conflicting requirements of the two types can be reconciled in a single design.

395. Grenade Identification.—The body color scheme to differentiate types of grenades is as follows: fragmentation grenades, yellow; chemical grenades, blue-gray, with superimposed red stripe or band to indicate gas or yellow stripe to indicate smoke filler; practice grenades, which have or are to have an explosive charge, blue; dummy grenades, black. For complete identification of chemical grenades, a symbol denoting the specific chemical agent, e.g., CN, HC, etc., and the word GAS or SMOKE, is stenciled thereon, together with the ammunition lot number.

CHEMICAL CANDLES

Chemical candles are employed both for screening and harassing effect. Their successful use is dependent upon favorable wind, weather, and terrain conditions. They consist of a thin metal container, a chemical filler, and a match head which can be ignited readily by friction. Candles may be fired in groups, electrically.

The Candle, Irritant, DM, M1, is standard in our service; it is designed for harassing effect rather than for obscuring purposes. Types no longer standard but still in use are the Candle, Lacrimatory, CN, and the Candle, Smoke, HC.

The smoke pot, HC, M1, has been developed to replace HC smoke candles and grenades. It is filled with 12.5 lb. of HC, equipped with a starting mixture, match head, and scratcher. It burns for approximately 6 minutes, producing a dense, white, non-irritant smoke.

Candles are marked for identification by distinctive colors, bands, and symbols, in the same manner as chemical grenades.

CHAPTER XVII

SMALL ARMS AND SMALL ARMS AMMUNITION

As used in the United States service, the term *small arms* embraces not only the hand and shoulder weapons of the individual soldier but also machine guns and automatic weapons of all sizes less than 20 mm. in caliber. Weapons of larger caliber are classified as cannon.

The earliest missile used by primitive man probably was a stone, first thrown by hand and later by use of a sling, which remained an important military weapon for many centuries. Piercing missiles such as the javelin and spear were developed in very ancient times; the simple bow, the first weapon to discharge a piercing missile, came into use almost as early as the sling and remained of military importance until the eighteenth century. The crossbow was a comparatively modern invention, but the principle of this weapon was employed in earlier engines of war such as the catapult and ballista, which played important parts in ancient wars.

The origin of fire arms is lost in the haze of antiquity. The discovery of the composition of gunpowder is credited to Roger Bacon in 1248, although incendiary and pyrotechnic mixtures were known in India, China, and Greece much earlier. There is no recorded use of fire arms, or of gunpowder as a propellant, before the beginning of the fourteenth century. By the end of the century the hand-gun appeared, derived from the early crude cannon.

MILITARY RIFLES

396. Development.—The earliest hand fire arm was nothing more than a short metal tube of large caliber mounted on a rod or stick. It was, of course, a smooth bore, muzzle-loading weapon; ignition of the charge was accomplished by applying to the touch hole a burning wick or "match." The weapon was inaccurate and of little military value. After a very few years of development, better barrels were available, of calibers reduced to 0.50 or 0.60 inch, mounted on stocks which permitted firing from the shoulder. The same ignition was employed, but the "match" had become a thin wick or taper, mounted on an

S-shaped lever called the "cock"; pressure of the finger on the lower end of the cock rotated the end bearing the burning match downward to the flash pan or touch hole. This weapon was called the match lock.

The disadvantages of this ignition system led to the development of the wheel lock, which provided a spring-driven serrated wheel which could be revolved against a piece of iron pyrites held by the cock, producing a shower of sparks to ignite the priming powder. Although the wheel lock eliminated the objectionable match, the mechanism was costly, complicated, and easily broken.

The simpler flint lock was developed in the seventeenth century, and remained standard for two hundred years. It did not disappear completely as a military weapon until after the close of our Civil War, when the percussion system of ignition came into general use. As the flint lock was finally developed, the flint was clamped in a spring-driven cock controlled by a trigger and sear. When the cock fell under the action of the spring, the flint struck a steel "hammer" which was hinged over the flash pan. The blow uncovered the pan and produced the sparks required for ignition of the priming powder.

The advantages of rifling were known, and rifling systems had been developed, long before it was practicable to adopt rifling in military weapons. The difficulty was in devising a rapid method of loading and a projectile which could be readily passed down the fouled bore but which would expand into the rifling when fired. The invention of the percussion primer early in the nineteenth century, and the development of the metal cartridge case which provided effective obturation, resulted in the adoption of the breech loading system. The use of rifling then became practicable in all weapons.

As weapons improved and better ammunition became available, the magazine rifle was developed to meet the demand for increased fire power. It provided a magazine which held several rounds of ammunition, and means for transferring them to the chamber. Reduction of caliber, improvement in propellants which permitted use of smaller charges, and reduction of size and weight of cartridges simplified the problem. After the period of our Civil War interchangeability of parts was provided.

The modern military rifle was perfected in all its essentials by about 1890. Since that time details have been refined, smokeless powder has replaced black powder, improved ammunition has been provided, and better metals have become available. The trend has been towards smaller calibers and higher velocities. Semi-automatic shoulder rifles have been developed which will probably replace the magazine rifle as it replaced the single shot weapon.

397. Characteristics of Modern Rifles.—The requirements for modern military rifles and characteristics of typical weapons are as follows:

Barrel.—Caliber about 0.30 in., muzzle velocity about 2700 f. s., accuracy life at least 10,000 rounds. Sufficient strength to withstand the high pressures, with the metal resistant to corrosion and erosion to the extent practicable. Of minimum length consistent with accuracy and development of requisite velocity. Where a single weapon is used for both mounted and dismounted troops, the barrel length is about 24 in.

Mechanism and Action.—Bolt action and magazine fed. The bolt action should be simple, fast, and require the minimum operating effort to insure the maximum rate and accuracy of fire. The bolt must have requisite strength, operate under adverse conditions, permit ready disassembly for repairs without use of tools, and incorporate all necessary safety features, including a positive breech lock during firing.

The magazine is located in the receiver, with a capacity of at least 5 rounds, readily and quickly filled by means of clips or chargers.

General.—The rifle should be as light as possible, and of minimum length, consistent with strength, accuracy, and development of desired velocity with service ammunition. The average weight is between 8 and 9 lb., and the length about 43 in.

The rifle should be operable under severe service conditions, dependable and long-lived, readily reparable by replacement of defective or worn parts, and should require the minimum training of personnel for its effective use.

It should have simple, sturdy sights, protected against injury, designed to permit accurate fire, with the rear sight located as close to the firer's eye as practicable and adjustable for range and windage. The rifle should be equipped with a simple sling and a sturdy bayonet.

398. U. S. Rifle, Caliber .30, Model of 1903.—(Fig. 350). This rifle is popularly referred to as the "Springfield" because it was developed and first manufactured at Springfield Armory. It is a breech loading magazine rifle of the bolt action type, weighing 8.69 lb. The principal parts or groups are the receiver, barrel, bolt, trigger guard assembly, and the stock.

Receiver.—This is the frame about which all other parts of the rifle are assembled. The breech end of the barrel is firmly fastened into the forward end of the receiver by means of a threaded section. These parts are never separated except at an arsenal, since the longitudinal location of the barrel in the receiver must be fixed accurately to secure the proper support of the cartridge when the gun is fired. The assembly of the gun is completed by clamping the wooden stock between the

receiver and the trigger guard by means of the two guard screws, and attaching the hand guard.

Barrel.—This is 24.006 in. long and contains 4 grooves. The twist of the rifling is uniform, 1 turn in 10 in. The muzzle is rounded to protect the rifling. The barrel is provided with a fixed stud for mounting the front sight and a fixed base for supporting the rear sight.

Bolt.—This is the breech mechanism of the rifle and must perform the functions of loading, locking, and extracting. It also houses the firing pin and firing pin spring which operate in conjunction with the trigger mechanism. On the bolt body, and integral with it, are two locking lugs, the safety lug, the bolt handle, and the extracting and cocking cams. The safety lug comes into play only in the event that the locking lugs yield or fail during firing.

The bolt is supported in the receiver with the bolt handle at the rear and to the right. Assuming the bolt to be open and in the rearmost position, the operations are as follows:

Loading and Locking the Breech.—As the bolt is moved forward, the lower edge of its face bears against the base of the top cartridge in the magazine, pushing it forward and into the chamber. During this operation the hook of the extractor is engaged in the extraction groove near the base of the cartridge. During the final part of the forward motion of the bolt, the sleeve lock strikes the receiver, and the sleeve, which supports the firing pin at the rear, is unlocked from the bolt body. The bolt handle is now rotated to the right and down, causing the rear surfaces of the locking lugs to ride on the cam surfaces leading to the locking recesses in the forward end of the receiver. The final forward motion of the bolt, due to the action of the cams, completes the seating of the cartridge and leaves it firmly supported for firing.

Opening the Breech.—The bolt handle is raised, rotating the bolt body and unlocking the breech by removing the locking lugs from the locking shoulders in the receiver. Just before the rotation of the bolt is stopped in the unlocked position, the extracting cam on the bolt comes into contact with the extracting cam in the receiver so that a mechanical advantage is provided for overcoming the resistance to extraction of the fired case. The limit of rotation having been reached, the bolt is withdrawn to the rear until the top locking lug comes into contact with the cutoff. In the meantime, the point of the ejector, extending into a slot in the top locking lug, has come into contact with the base of the cartridge with sufficient force to free it from the grip of the extractor and to cause it to fly out of the receiver.

Cocking.—The unlocking rotation of the bolt causes the cocking cam, a V-shaped opening in the rear underside of the bolt, to force the firing

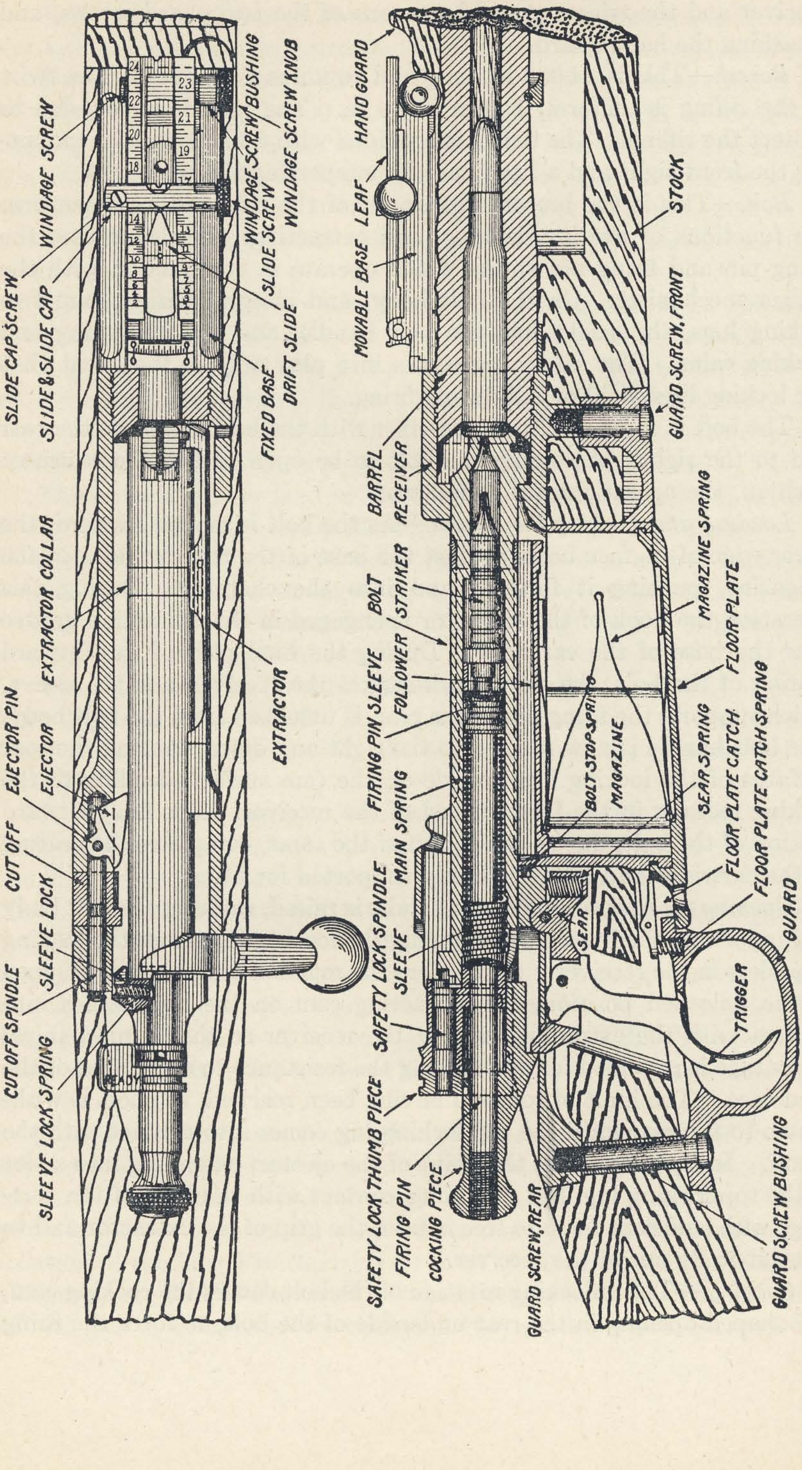


FIG. 350.—Mechanism of the United States Rifle, Caliber .30, Model of 1903.

pin to the rear, compressing the firing pin spring, and drawing the point of the striker within the body of the bolt. Rotation of the firing pin itself is prevented by the lug on the cocking piece projecting through the slot in the sleeve into a groove in the receiver. At the end of rotation of the bolt, all parts are locked together by the sleeve lock engaging its notch in the bolt. The cocking operation is completed when the bolt is moved forward again. Just before the bolt reaches its forward position, the toe of the cocking piece lug comes against the sear, which extends above the bottom of the groove in the receiver. Further forward movement of the bolt, most of which is due to the action of the locking cams, completes the compression of the firing pin spring. The locking rotation of the bolt also brings the V-shaped opening opposite the cocking piece lug, so as to permit the firing pin to fly forward freely when the sear is withdrawn.

Cutoff.—When the cutoff is down, showing "Off," the rearward motion of the bolt is stopped before its face has cleared the base of the top cartridge. Thus, when the bolt moves forward, it is not able to push the top cartridge out of the magazine. This provision was originally made so that the rifle could be fired "single shot," each round being loaded by hand, keeping the five cartridges in the magazine as a reserve. When the cutoff is up, showing "On," the bolt is allowed to move far enough to the rear to engage the base of the next cartridge for loading. After the last cartridge has been fired and ejected, forward motion of the bolt is prevented by the magazine follower which has been raised high enough to interfere. Blocking the bolt in this manner makes certain that the rifleman will realize that the magazine is empty, even in the excitement of battle. The third position of the cutoff, midway between "On" and "Off," permits the withdrawal of the bolt from the receiver.

Trigger Mechanism.—The trigger mechanism consists of the trigger, sear, sear spring, and two pins. The sear, as shown in Fig. 350, is hinged in the receiver by means of the sear pin. The sear spring is so mounted that it holds the nose of the sear above the bottom of the groove in the receiver. In this position the sear nose engages the toe of the cocking piece lug, thus holding the firing pin to the rear against the pressure of its spring. The trigger is mounted on a pin in a slot through the sear so that its rounded upper surface bears against the bottom of the receiver. When the trigger is pulled to the rear, it has comparatively free movement until its rear point, or "heel," comes into contact with the receiver. This motion of the trigger is called *slack*. Continued pulling of the trigger causes the sear to revolve about its pin in a counterclockwise direction so that its nose is withdrawn from contact with the cocking piece lug. This combined motion of the trigger and

sear is called *creep*, at the end of which the firing pin is released to fly forward against the primer.

Safety Lock.—This is mounted on a pin at the top rear of the sleeve. When rotated to the right, two ridges on the lock enter corresponding grooves in the cocking piece so as positively to prevent any motion of the firing pin. The safety lock operates only when the firing pin is in the rearmost position, with the spring fully compressed.

The Sights.—The front sight is of the blade type and is fixed in a slot in the movable stud. This, in turn, is fixed in an undercut slot in the fixed stud at the muzzle.

The rear sight is of the leaf type. The leaf is hinged to the movable base which is supported in the fixed base at the breech. Controlled lateral movement of the movable base is accomplished through the windage screw. A scale is provided at the rear, each division of which corresponds to a lateral deviation of 4 in. at 100 yd. The leaf of the rear sight is graduated from 100 to 2850 yd. The slide assembly, which may be adjusted on the leaf for the desired range, provides a peep sight and two open or notch sights. The peep sight is habitually used. When the sight leaf is folded down against the base another open sight, called the "battle sight," is available. The setting corresponds to a range of 441 yd. regardless of the position of the slide.

The peep sight is contained in the *drift slide* which is moved to the left by a groove in the leaf as the slide is raised. This automatically corrects for drift to the right at each range. Below 500 yd. the drift slide points the muzzle to the right of the target to compensate for an inherent tendency of the gun to jump to the left at the instant of firing. This jump is thought to be due to a natural vibration of the barrel and has been found to be nearly constant in magnitude.

AUTOMATIC AND SEMI-AUTOMATIC WEAPONS

An automatic weapon is one that loads, fires, extracts, ejects, and reloads, continuing the cycle as long as the firing mechanism is held in the proper position. The operation after loading and firing the first round is entirely automatic, the necessary energy being supplied by the ammunition and stored in springs for the performance of counter-recoil and loading operations. The semi-automatic weapon is similar, but the trigger must be pulled for each round fired. Many automatic weapons are designed to permit semi-automatic fire.

399. Development.—The development of automatic features and of full automatic weapons was in response to the demand for increased fire power. The early weapons employed multiple barrels on a single

mount, which could be fired simultaneously. Other arrangements which were developed permitted the firing of multiple barrels successively, or brought multiple chambers successively to a single barrel. These did no more than increase the volume or rapidity of fire. They were very heavy and cumbersome.

The development of automatic weapons was hastened by the invention of the percussion primer, the adoption of breech loading, and the introduction of complete rounds of ammunition assembled in a metal cartridge case. The first practicable machine gun was the Gatling, invented by Dr. Gatling of Chicago about the time of our Civil War. It provided a number of barrels arranged symmetrically about a central axis, which could be loaded, rotated successively to the firing position, and fired, by turning a hand crank. The ammunition was fed from a hopper by gravity. The operation of the weapon was purely mechanical. It was an important rapid-fire weapon for many years; its adoption was followed by others of the same general type, which in effect combined in one mount a considerable number of breech-loading rifles that could be loaded and fired mechanically.

In 1884 Sir Hiram Maxim, an American engineer, produced the first truly automatic machine gun. It employed a single barrel, and utilized the principle of recoil operation to secure continuous and automatic functioning so long as the trigger was held down. The ammunition was fed into the chamber by use of a fabric belt and automatic-loading mechanism. This weapon was an immediate success; the soundness of its design and principle of operation were immediately recognized. It revolutionized machine gun tactics and stimulated the development of other automatic types. In modified and improved form it still remains one of the important military weapons.

The principle of gas operation, utilizing a small portion of the expanding powder gas, was first successfully employed by John M. Browning, an American, who brought out the Colt machine gun in 1889. This was followed by the Hotchkiss, employing the same system of operation.

The machine gun and other automatic weapons first demonstrated their great effectiveness in the World War, and exercised a profound effect upon tactics. Many new designs appeared as well as improved types of earlier weapons. This development has continued since the war, and the various types, characteristics, and uses have become well established.

400. Characteristics of Automatic Weapons.--In addition to assured mechanical operation even under adverse service conditions, the efficient automatic weapon must fulfill other requirements. The desired characteristics will vary with the size and caliber of the weapon, the par-

ticular use for which it is designed, the type of mount for which intended, etc. Certain of these characteristics are:

1. It must be capable of delivering accurate and sustained fire. The rate of fire must satisfy tactical requirements. It must be able to use the standard service types of ammunition used in other weapons of the same caliber.

2. It must be as light as possible, consistent with stability of fire. The weight is not so important where the question of mobility is not involved, but size (bulk) may be a highly important factor. The light gun must be able to go anywhere a soldier on foot can go and engage any class of target.

3. The mechanism should be simple to operate, safe in action, and economical to maintain; for field maintenance, parts should be accessible for cleaning, repair, and replacement. Manufacture should be simple and economical.

401. Design Features.—The following features are incorporated in the design of standard automatic weapons:

1. A system of automatic operation, utilizing power developed by the cartridge but without detriment to its ballistics.

2. A means for storing the energy required for counter-recoil and loading operations.

3. A positive feed mechanism, means for positive extraction and ejection of spent cases, and provision for ejection of empty fabric belt, links, or magazine.

4. A means of firmly supporting the cartridge during firing and of insuring effective breech closure until the gas pressure has dropped to safe limits.

5. A firing mechanism with adequate safety features and, preferably, with means for selection of automatic or single shot action, and for adjustment of rate of automatic fire.

6. An adequate system of cooling, consistent with weight requirements and the projected tactical utilization of the weapon, to permit maximum sustained fire.

7. Provision for ready replacement of worn barrels, without requiring special adjustment for head space.

402. Types of Mechanisms.—There are three basic types, *blowback*, *recoil operated*, and *gas operated*. The names are indicative of the principle of operation employed. Within each class are various subgroups, and certain weapons may employ a combination of operating principles.

403. Blowback Operation.—In this system, the operation of the mechanism is effected through the rearward projection of the spent cart-

ridge case under the action of the expanding powder gases. The force is sufficient to force the bolt or breechblock open, against the resistance of a spring which stores the energy necessary for counter-recoil and loading operations. The cartridge case is generally lubricated to facilitate its rearward projection from the chamber, which is a serious disadvantage in a military weapon. In the blowback system provision must be made for effective breech closure until the gas pressure has dropped to safe limits. The classification of the various subtypes of this system is based upon the method employed to resist premature breech opening.

404. Simple Blowback.—This system is the simplest; it provides no means for positively locking the breech in the firing position. The inertia of the breechblock and other moving parts is depended upon to keep the cartridge case seated in the chamber for the short period of time necessary for safety. This system is not adapted to weapons using high-powered ammunition, but can be used in weapons of low power and small caliber.

405. Retarded Blowback.—In military and other weapons using high-powered ammunition, mechanical means of delaying backward movement is employed in place of the inertia element of the simple blowback mechanism. This is accomplished by various methods, including crank and connecting rod, linkage with rolling contact, sliding or rotating wedge, and others, each of which delays the opening of the breech by introducing a mechanical disadvantage.

Crank Delay.—This principle is illustrated in Fig. 351, top. The connecting rod is pinned to the breechblock; a fixed pin connects the crank to a non-recoiling part of the weapon body. At the instant of firing, the two parts are at a very small angle with each other, almost at dead center, and practically all the force exerted by the cartridge case on the breechblock is transmitted through the fixed pin to the body of the weapon. The component perpendicular to the crank will cause rotation about the fixed pin. In the early stages this angular motion is accompanied by little rearward movement of the breechblock, and the opening of the breech is delayed. As the angle between the rod and crank increases, the momentum of the moving parts and the remaining gas pressure are sufficient to complete the backward movement of the block against the resistance of the return spring.

Rolling Contact Delay.—This mechanism is illustrated in the lower part of Fig. 351. The forward member is pinned to the breechblock and the rear member to a fixed part of the weapon; they are linked together as shown. In the firing position, the point of contact between the two cylindrical surfaces and the line connecting the link pins and the fixed

pin are only slightly above the line of thrust of the cartridge case against the breechblock. Breech opening is thus retarded. Also, the cylindrical contact surfaces are so designed that considerable upward movement of the joint may take place while the point of contact still remains close to the line of thrust. As the joint continues to rise, however, the

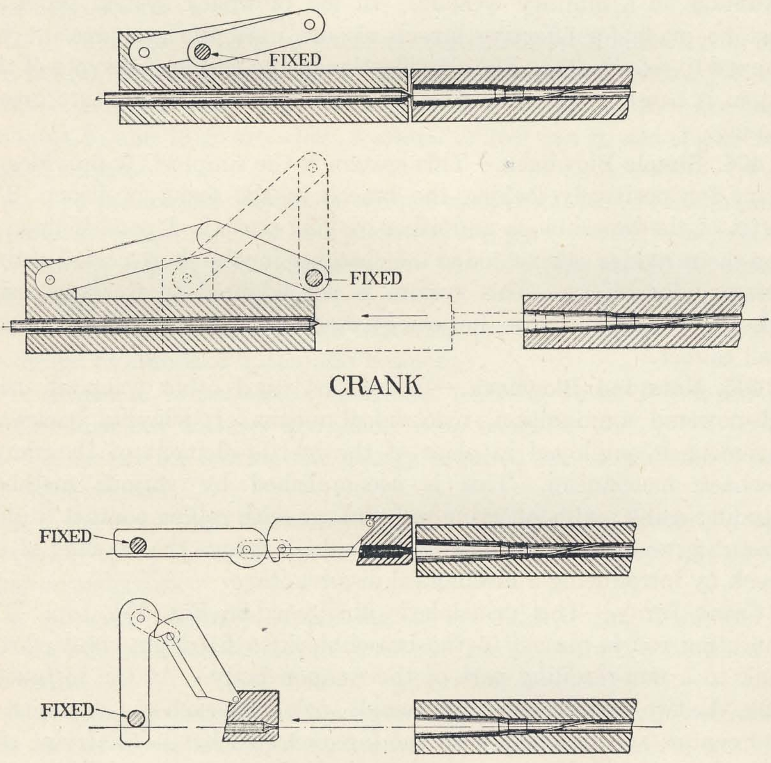


Fig. 351.

breechblock moves to the rear, opening the breech and compressing the return spring.

Rotating or Sliding Wedge. (*Blish Principle*).—An adaptation of this principle is illustrated in Fig. 352. This mechanism depends upon friction between inclined bearing surfaces to keep the breech closed while the breech pressure is high, but is so designed that at relatively low pressures the component forces parallel to the bearing surfaces will cause sliding, thus unlocking the breech. This condition is obtained by providing locking surfaces at an angle of approximately 75° with the axis

of the bore. The application may be in the form of an interrupted thread having the proper angle, as illustrated, or a block sliding in

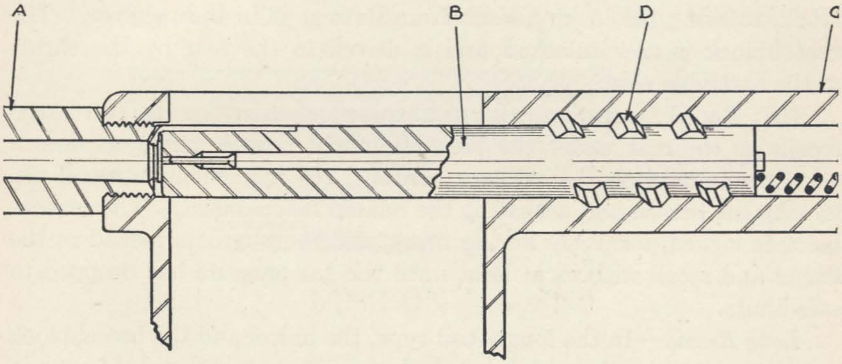


FIG. 352.

grooves at the proper angle with the line of thrust. In either case, the bearing surfaces are lubricated to insure uniformity of action.

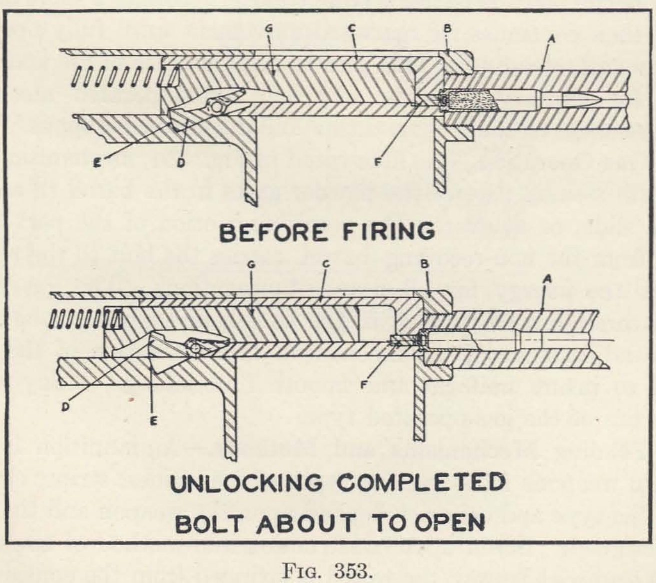


FIG. 353.

406. Primer Actuation.—This is essentially a delayed blowback mechanism, except for the introduction of a positive breech lock. As illustrated in Fig. 353, the breechblock C is locked in the firing position

by the latch *D*. In firing, the primer cup is blown backward from its seat in the cartridge case, striking a sharp blow on the firing pin *F*, which in turn drives to the rear the actuator *G* located within the breechblock, rotating the locking latch from its seat *E* in the receiver. The breechblock is now unlocked, and is driven to the rear by the thrust of the cartridge case.

407. Recoil Operation.—In mechanisms of this type the gun barrel recoils to the rear under the pressure of the powder gases, as does a cannon mounted on the artillery carriage, the movement in recoil unlocking the breech and actuating the related mechanisms. The breechblock is locked positively during firing, and must remain locked to the barrel and recoil with it, at least until the gas pressure has dropped to safe limits.

Long Recoil.—In the long recoil type, the barrel and the breechblock or bolt recoil the entire distance together. The bolt is then held open in the recoiled position as the barrel goes forward, a sufficient length of time to permit extraction of the spent case and reloading. The rate of fire is necessarily slow.

Short Recoil.—In weapons of the short recoil type, the bolt is unlocked from the barrel and the barrel is stopped after recoiling a short distance; the bolt then continues its rearward movement until fully opened for extraction and reloading. This permits a higher rate of fire and is more suitable for military weapons. Typical recoil-operated mechanisms will be discussed in connection with standard service weapons.

408. Gas Operation.—As illustrated in Fig. 354, mechanisms of this type utilize a small part of the powder gases in the barrel to actuate a piston, a slide, or a lever. The resulting motion of the part unlocks the bolt from the non-recoiling barrel, carries the bolt to the rear, and transmits the energy for all required operations. The gas may be diverted through a small vent in the barrel, or tapped at the muzzle. Accurate adjustment of the mechanism and regulation of the port is essential to insure uniform and smooth functioning. Many military weapons are of the gas-operated type.

409. Feeding Mechanisms and Methods.—Ammunition is fed to automatic weapons from various types of magazines, strips, clips, and belts. The type and capacity depend upon the weapon and the use for which designed. Based upon construction and method of ammunition insertion and withdrawal, the round is stripped from the container and pushed into the chamber by the forward motion of the bolt, or withdrawn from the container during the backward movement of the bolt, and supported and carried forward into the chamber during the counter-recoil movement. After each round is withdrawn, the feed mechanism

effects the necessary movement of the remaining ammunition supply to bring the next round in position for loading.

Magazines.—The box magazine is of limited capacity, usually from 7 to 20 rounds, depending upon the caliber and type of the weapon. It

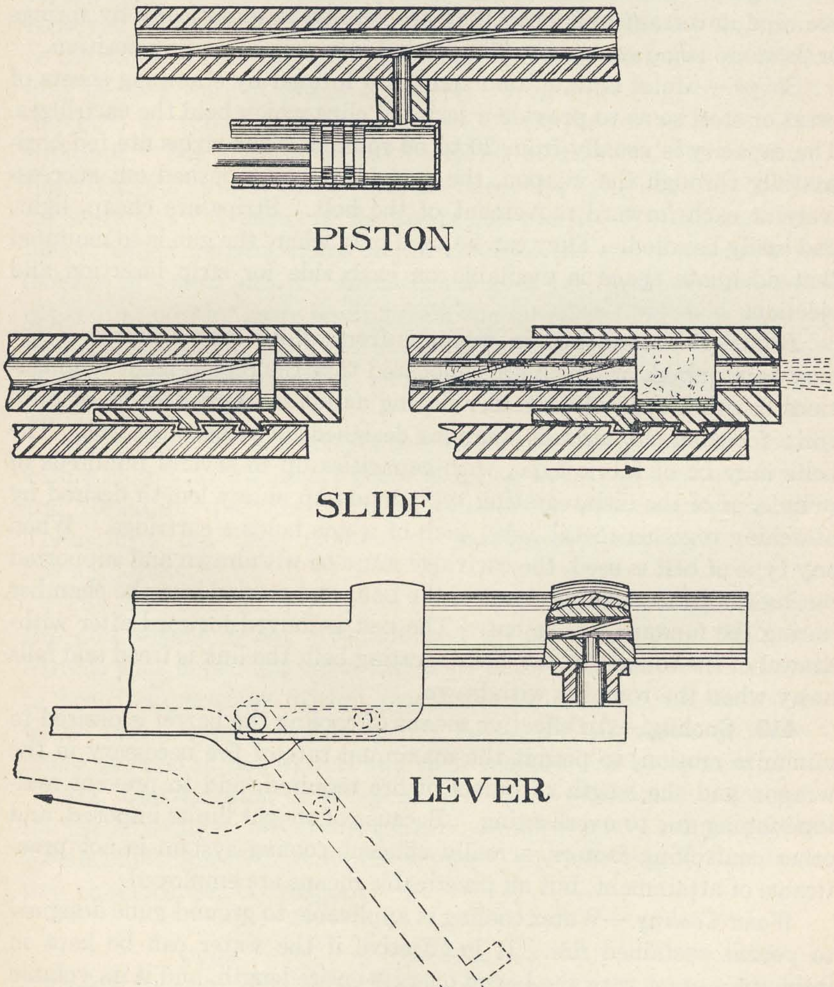


FIG. 354.

is inserted in the side, top, or bottom of the receiver. The ammunition is pushed out or stripped by the forward movement of the bolt, and the remaining cartridges are then forced toward the open end of the magazine by followers or springs.

Magazines may be designed to remain attached to the weapon, instead of being removed and replaced when empty, or the magazine may be formed within the receiver of the weapon. The ammunition is usually loaded into such magazines in clips, which are ejected when empty.

Larger circular or drum magazines, with capacities up to 100 rounds, are used in certain weapons; they are rotated automatically by springs or pawls to bring each succeeding round into proper loading position.

Strips.—Metal ammunition strips are formed by stamping sheets of brass or steel so as to provide a series of clips which hold the cartridges. The capacity is usually from 20 to 50 rounds. The strips are fed horizontally through the weapon, the cartridges being pushed out successively at each forward movement of the bolt. Strips are cheap, light, and easily handled. They can be used only where the gun is so mounted that adequate space is available on each side for strip insertion and ejection.

Belts.—Belts are used in weapons from which longer bursts of fire may be required, or which are so located that the replacement of magazines or other type of container during action is impracticable or difficult; for example, aircraft weapons designed for remote control. The belts may be of fabric type, with capacities up to several hundreds of rounds, or of the disintegrating type, made up in any length desired by attaching together metal links, each of which holds a cartridge. When any type of belt is used, the cartridge must be withdrawn and supported during the rearward movement of the bolt, and carried into the chamber during the forward movement. The belt is moved forward after withdrawal of the round; in the disintegrating belt, the link is freed and falls away when the round is withdrawn.

410. Cooling.—An effective means of cooling the barrel is desired to minimize erosion, to permit the maximum rate of fire necessary in the weapon and the length of bursts of fire required, and to prevent malfunctioning due to overheating. Because of weight limits imposed, and other controlling factors, a really efficient cooling system is not practicable of attainment, but all practicable means are employed.

Water Cooling.—Water cooling is applicable to ground guns designed to permit sustained fire. It is effective if the water can be kept in intimate contact with the barrel over its entire length, and if its volume is sufficient. If boiling is to be prevented, means must be provided for circulation of cooled water from an outside reservoir; otherwise, provision must be made for the escape of steam and replacement of the lost water. For operation in very cold weather, liquids other than water, with lower freezing points, are employed to prevent damage due to freezing when the gun is not in action.

Water cooling adds weight and reduces mobility. In weapons of the recoil-operated type, water-tight packing and glands must be provided to permit movement of the barrel relative to the jacket.

Air Cooling.—This is the simplest method and its use results in considerable saving in weight; it is not so effective as water cooling, however. In aircraft guns, so mounted as to be exposed continuously to the air blast resulting from the plane's motion, relatively light barrels may be used without excessive erosion. In ground weapons, and those mounted in vehicles, simple exposure of the barrel to the air is not sufficient. The addition to the barrel of integral fins, ribs, or rings, or provision of a knurled surface, assists in cooling by increasing the radiating surface. The barrel of the Lewis gun was fitted with an aluminum jacket finned longitudinally on the outside, the whole assembly being encased in a steel jacket. An attachment at the muzzle end caused the expanding powder gases issuing from the muzzle to induce a flow of air from the rear of the outer jacket along the aluminum fins. Cooling was effective during firing only; temperatures were excessively high when firing ceased.

Other attempts have been made to cool the barrel by surrounding it with a closely fitting jacket made of metal with high heat conductivity and radiation qualities, such as aluminum and magnesium alloys. These have not been particularly satisfactory, especially in recoil-operated guns.

The most satisfactory results have been obtained, where increase in size and weight is not objectionable, by providing very thick heavy barrels, thus depending upon increased mass and greater heat capacity to keep temperatures within reasonable limits. In the lighter guns, where strict weight limitations are necessary, provision is made for quick removal of hot barrels and their replacement by spares.

411. Classification of Weapons.—Tactical requirements are met by the use of weapons of various calibers, on appropriate mounts, designed specifically to meet these requirements. The following is a representative classification of weapons:

Class	Caliber	Employment
Automatic Cannon	20 mm. and larger	Ground, tank, and aircraft weapons for antiaircraft and anti-tank use.
Aircraft Machine Gun	.30 in. to .50 in.	Fixed and flexible aircraft armament.
Antiaircraft Machine Gun	.30 in. to .50 in.	For local antiaircraft defense.
Tank Machine Gun	.30 in. to .50 in.	In armored combat vehicles.

Class	Caliber	Employment
Anti-tank Machine Gun	.50 in.	For ground defense against armored vehicles.
Heavy Machine Gun (Ground)	.30 in.	All types of targets; mobility limited by weight.
Light Machine Gun (Ground)	.30 in.	All types of targets; lightness permits use by assault troops.
Machine Rifle / Automatic Rifle	.30 in.	Essentially the same as the light machine gun; classes becoming merged.
Semi-automatic Rifle	.30 in.	Shoulder weapon; may replace magazine rifle.
Submachine Gun	.45 in.	Short range combat.
Automatic Pistol	.45 in.	Individual hand weapon.

412. Standard Weapons.—The standard weapons employed in the United States service include:

Machine Guns.

Caliber .30.

Water cooled.	Browning, M1917.
Air cooled.	Browning, M1919A4.
	Browning, M2, heavy barrel.
	Browning, M1918M1, aircraft.
	Browning, M2, aircraft.

Caliber .50.

Water cooled.	Browning, M1921 and M1921A1.
	Browning, M2.
Air cooled.	Browning, M1921.
	Browning, M2, heavy barrel.
	Browning, M2, aircraft.

Caliber .22. M1. (Modified caliber .30 Browning, M1917.)

Semi-automatic Weapons (exclusively* or selectively).

Caliber .30.	Browning Automatic Rifle, M1918, M1918A1.
	Browning Machine Rifle, M1922.
	U. S. Rifle, M1.*
Caliber .45.	Automatic Pistol, M1911, M1911A1.*
	Thompson Submachine Gun, M1928A1.

A description of the more important types follows.

413. Browning Machine Gun, Caliber .30, M1917.—This is the basic machine gun of our service; many modifications and adaptations of its mechanism appear in more recent designs. It is a recoil-operated weapon, of the short recoil type, belt-fed and water-cooled. It has a

cyclic rate of fire of approximately 600 rounds per minute, with any type of service caliber .30 ammunition. The water jacket surrounding the barrel has a capacity of about 7 pints.

The barrel is supported in the receiver by the trunnion block, and in the forward end of the water jacket by the muzzle bearing, being free to move longitudinally in recoil and counter-recoil. The breech end of the barrel is screwed to the barrel extension which supports the bolt in the firing position, where it is held by the breech lock.

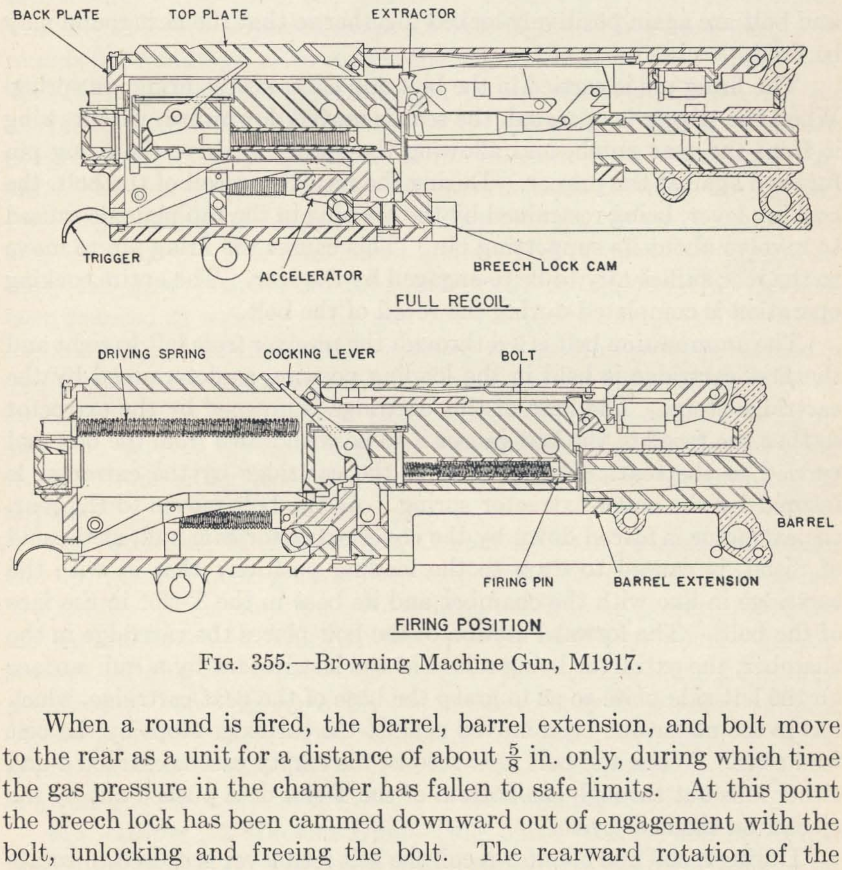


FIG. 355.—Browning Machine Gun, M1917.

When a round is fired, the barrel, barrel extension, and bolt move to the rear as a unit for a distance of about $\frac{5}{8}$ in. only, during which time the gas pressure in the chamber has fallen to safe limits. At this point the breech lock has been cammed downward out of engagement with the bolt, unlocking and freeing the bolt. The rearward rotation of the accelerator, under the action of the recoiling barrel extension, accelerates the movement of the bolt and enables it to extract the spent case from the chamber and compress the return spring; the bolt is stopped by a buffer in the back plate. The recoil of the barrel extension is stopped by the compression of a barrel plunger spring, and it is locked in its recoiled position by the accelerator.

In counter-recoil, the bolt is moved forward by the compressed driving spring and returns to its position on the barrel extension. In so doing, the lugs on its lower side strike the accelerator, rotating it forward. This unlocks the barrel extension from the lock frame and causes it to move forward, the force of the barrel plunger spring being added to that of the driving spring which is now being applied to the barrel and barrel extension through the bolt. The last motion of counter-recoil causes the breech lock to ride up on the ramp formed by the breech lock cam and to enter a recess in the bottom of the bolt. Thus the barrel extension and bolt are again positively locked together so that the next round may be fired.

The firing pin is carried in the bolt and contains the firing pin spring. When the trigger is operated, the sear is moved downward, withdrawing it from the sear notch, and allowing the spring to drive the firing pin forward against the primer. During the resulting recoil of the bolt, the cocking lever, being restrained by the opening in the top plate, is caused to revolve about its supporting pin. This causes the firing pin to move to the rear sufficiently to be re-engaged by the sear. The entire cocking operation is completed during the recoil of the bolt.

The ammunition belt is fed through the receiver from left to right and the first cartridge is held in the loading position as determined by the cartridge stops. The base of this cartridge is grasped by the extractor so that the recoil of the bolt causes it to be withdrawn from the belt and carried to the rear. Engagement of the cartridge by the extractor is insured by the cover extractor spring. As the bolt moves to the rear, the extractor is forced down by the cover extractor cam and, at the end of recoil, is caused to drop to the loading position; that is, with the cartridge in line with the chamber and its base in the T-slot in the face of the bolt. The forward motion of the bolt places the cartridge in the chamber, the extractor being raised at the last instant by a cam surface on the left side plate so as to grasp the base of the next cartridge, which has in the meantime been moved against the cartridge stops by the belt feed pawl. When the bolt next recoils, the empty case is extracted and either falls out through the bottom of the T-slot or is pushed out by the ejector on the next cycle.

During recoil and counter-recoil the belt feed lever is caused to rotate about its pivot pin by the motion of the stud on its rear end as it follows the cam groove cut in the top of the bolt. This lateral oscillation is applied to the belt feed pawl which thus feeds the ammunition belt into the receiver at the rate of one cartridge for each cycle of operation.

This machine gun continues to fire as long as the trigger is held in the

firing position. It can be seen from Fig. 355 that the sear cannot be operated by the trigger until the mechanism is far enough forward for the bolt to be locked in the firing position by the breech lock.

414. Other Browning Machine Guns, Caliber .30.—The mechanisms of the other caliber .30 machine guns listed in Section 412 are the same as that of the M1917, with such slight modifications as were necessary to adapt them for special uses. For example, the tank machine gun is air cooled and has a heavy barrel. This results in a slightly reduced rate of fire, but permits the gun to be mounted in armored vehicles. The mechanism is adjusted to give a rate of fire of not more than 400 rounds per minute so as to reduce the amount of heat to be dissipated. The M1918M1 aircraft machine gun, on the other hand, has had its mechanism lightened by cutting away unnecessary metal wherever possible, increasing its cyclic rate of fire to about 1000 rounds per minute. This gun is also air cooled but uses the same barrel as the M1917.

The Browning Machine Gun, Caliber .30, M2, is a redesign of the original weapon. The mechanism and method of operation are essentially the same, but the individual parts and the gun as a whole have been reduced in weight. This gun was originally intended for aircraft use and the reduction of the weights of the moving parts permitted a cyclic rate of fire of 1200 rounds per minute. All parts of the feeding mechanism were mounted on easily removable pins and the receiver and bolt were so arranged that the ammunition could be fed into the receiver from either side; this simplified the problem of mounting in airplanes.

415. Browning Machine Guns, Caliber .50.—In general, the design and operation of these guns are the same as for the caliber .30 weapons. The caliber .50 ammunition is, of course, much more powerful and the mechanism has been strengthened in order to withstand the greater stresses. Owing to the increased energy of the recoiling parts it has been necessary to add a spring hydraulic buffer to stop their recoil without excessive jar or strain. This buffer has the added advantage of being adjustable so as to vary the cyclic rate of fire. Ordinarily the caliber .50 machine gun has a rate of fire of 550 to 600 rounds per minute.

416. Caliber .22 Machine Gun.—(Fig. 356.) This is another modification of the M1917 Browning Gun, designed to facilitate training by making machine-gun gallery practice possible and inexpensive. In this weapon, the barrel P remains stationary and is not attached to the barrel extension. The cartridge is seated in a chamber C screwed to the barrel extension. On firing, the gas pressure in the space between the barrel and the chamber forces the chamber and attached barrel extension to

the rear, driving the bolt T backward. Otherwise there is little change in the design or operation of the M1917 mechanism.

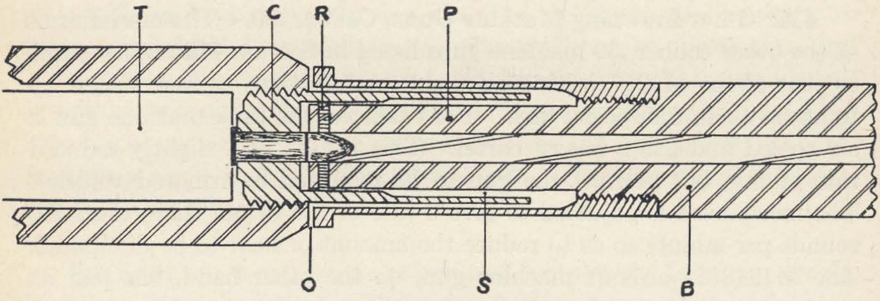


FIG. 356.—Caliber .22 Machine Gun.

417. Browning Automatic Rifle, Caliber .30, M1918.—This weapon weighs about 15 lb., is gas operated, air cooled, magazine fed. The port, located under the barrel about 6 in. in rear of the muzzle, permits a small portion of the gas to enter the cylinder. The resulting motion of the piston, acting through the slide (Fig. 357), moves the bottom of

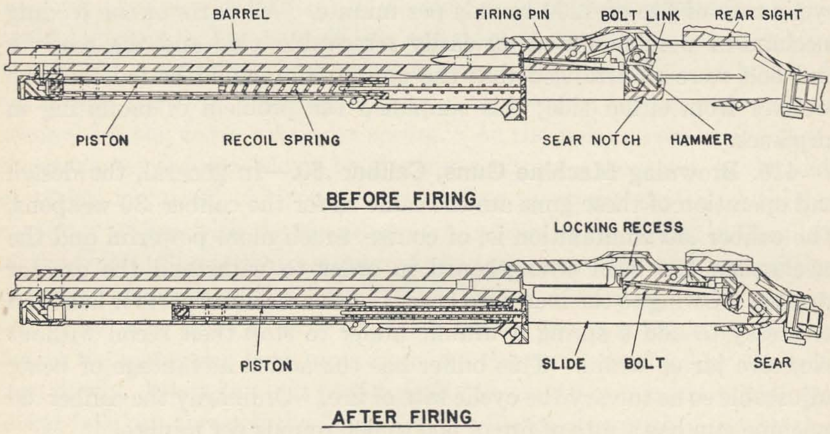


FIG. 357.—Browning Automatic Rifle.

the bolt link to the rear. This causes the bolt lock to be withdrawn from the recess in the top of the receiver and then to follow the link in recoil, pulling the bolt with it and opening the breech so as to extract the empty case. The recoiling parts are stopped when the rear end of the slide strikes against the resilient buffer in the butt. At this time, the sear nose engages in the notch in the bottom of the slide, holding

against the pressure of the spring which has been compressed during recoil. To fire another shot, the trigger must be pulled to disengage the sear so that the mechanism can be moved forward by the pressure of the recoil spring acting through the piston rod and slide. As the bolt moves forward it strips the next cartridge out of the magazine and seats it in the chamber. At this time, the forward motion of the bolt ceases and the continued motion of the slide causes the bolt supports to break the joint between the bolt lock and bolt, forcing the bolt lock upward into the locking recess. The final forward motion of the slide causes the hammer to strike the firing pin, which was exposed by raising the bolt lock. This construction makes it practically impossible to fire the cartridge until the breech is positively locked.

It is possible, by moving a stop out of the way, to allow the trigger to have enough motion to hold the sear out of engagement with the sear notch. This results in automatic fire until the magazine is emptied or the trigger is released. The same stop, moved in the opposite direction, acts as a safety by preventing any motion of the trigger.

418. Browning Machine Rifle, Caliber .30, M1922.—This is essentially the same as the automatic rifle. The major design difference is the substitution of a slightly heavier barrel with cooling fins around the breech so as to permit firing longer bursts. This weapon is habitually fired from a bipod.

419. Thompson Submachine Gun, Caliber .45, M1928A1.—This is an air-cooled weapon, operated on the delayed blowback principle. It uses the same ammunition as the service automatic pistol; it is fed either from a drum-type magazine of 50-round capacity, or from a 20-round box type. The operating mechanism is illustrated in Fig. 358.

The bolt is held in the firing position by the lock G; the parts B rest in the slot F of the bolt, and the projecting lugs C bear against locking surfaces D formed on the inside of the receiver. The rearward thrust of the cartridge case is transmitted from the bolt to the lock, and from the lock to the locking surfaces of the receiver. The angle of the latter is so designed that there will be no movement of the lock while the gas pressure is high, but it will slide up and clear the locking surface, freeing the bolt, when the pressure has dropped to safe limits. As the lock rises in the slot F of the bolt, its cross piece G enters the recess H in the actuator, locking these members together during recoil. The return spring bears against the downward projecting lug of the actuator, and is compressed during the rearward movement.

In the forward movement, under the action of the spring, the actuator carries the bolt to its closed position, the lugs C of the lock come into

contact with the locking surfaces *D*, and are cammed downward into the locked position.

The mechanism may be set for automatic fire, in which the sear remains in its lower position and cannot enter the sear notch on the bolt so long as the trigger is depressed; or it may be set for semi-automatic or single-shot action, in which case the sear engages the bolt after each shot and must be released by a pull on the trigger.

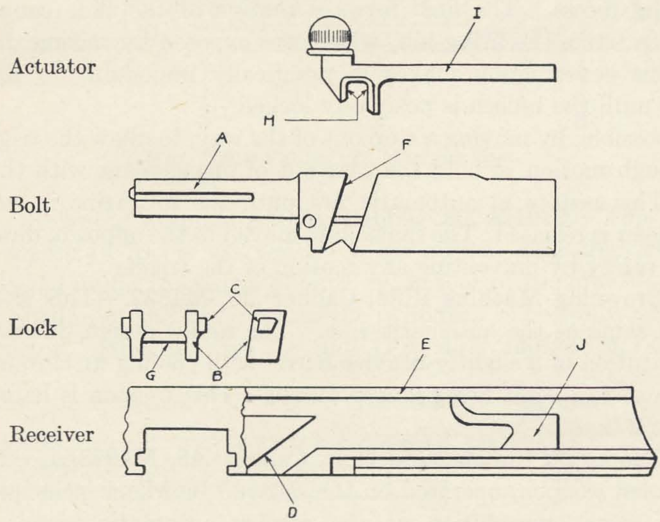


FIG. 358.—Operation of Thompson Submachine Gun.

420. Automatic Pistol, Caliber .45, M1911.—This is a short-recoil operated, magazine-fed hand weapon, illustrated in Fig. 359. The barrel (*A*) and the slide (*B*) are locked together in the firing position by the lugs (*C*) on the barrel which engage in corresponding grooves in the slide. The rear part of the slide functions as a breechblock. At the beginning of recoil, the barrel and slide move to the rear together, but after slight movement the barrel is drawn down by the link (*D*), disengaging the locking lugs and permitting the slide to continue to the rear alone. The barrel, in the meantime, strikes against the shoulder of the receiver and comes to an abrupt stop. Further recoil of the slide extracts and ejects the empty case, and causes the hammer to rotate to the cocked position, where it is engaged and held by the sear. At the end of recoil, the slide is forced forward by the compressed spring (*E*) and, just before the end of counter-recoil, strikes against the rear end of the barrel. The barrel is forced forward and upward, as constrained

by the link, so that the locking lugs are re-engaged. During counter-recoil the bottom of the slide strips the next cartridge out of the magazine and places it in the chamber.

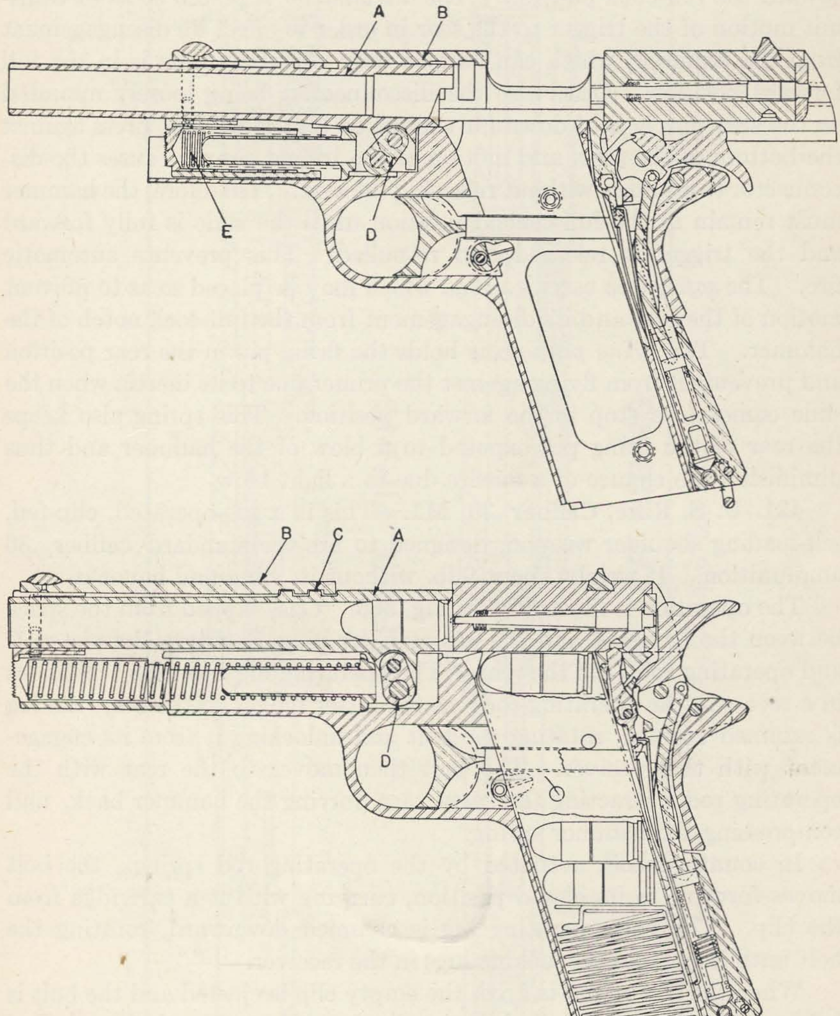


FIG. 359.—Automatic Pistol, Caliber .45.

Several safety features are provided to prevent accidental firing. A lug on the *grip safety* prevents rearward movement of the trigger unless the grip safety has been pushed into the butt, as would happen

when the pistol has been grasped for firing. The hammer is provided with a *half-cock notch*, which is so deep that the sear cannot be disengaged by pulling the trigger; it can be released only by revolving the hammer toward the full-cock position. The *disconnector* is placed so as to transmit motion of the trigger to the sear in order to effect its disengagement from the hammer, which can happen only when the slide is in the full forward position. Otherwise the disconnector, being loosely mounted on the sear pin, is held down far enough so that it will not press against the bottom of the sear, and motion of the trigger simply causes the disconnector to oscillate without releasing the sear. Therefore, the hammer must remain in the full-cocked position until the slide is fully forward and the trigger is released and re-pulled. This prevents automatic fire. The *safety lock* carries a stud which may be placed so as to prevent motion of the sear and its disengagement from the full-cock notch of the hammer. The *firing pin spring* holds the firing pin in the rear position and prevents it from flying against the primer due to its inertia when the slide comes to a stop in the forward position. This spring also keeps the rear of the firing pin exposed to a blow of the hammer and thus diminishes the chance of a misfire due to a light blow.

421. U. S. Rifle, Caliber .30, M1.—This is a gas-operated, clip-fed, self-loading shoulder weapon, designed to fire the standard caliber .30 ammunition. It weighs about 9 lb. without its sling and bayonet.

The operation is illustrated in Fig. 360. Gas, tapped from the space between the barrel *A* and the gas cylinder plug *B*, drives the piston *C* and operating rod *D* to the rear. The operating lug *E* on the bolt slides in a recess in the operating rod; as the latter moves to the rear, the lug is cammed upward, rotating the bolt and unlocking it from its engagement with the receiver. The bolt then moves to the rear with the operating rod, extracting the spent case, forcing the hammer back, and compressing the hammer spring.

In counter-recoil, actuated by the operating rod springs, the bolt moves forward to its closed position, carrying with it a cartridge from the clip. The bolt operating lug is cammed downward, rotating the bolt until it engages the locking lugs in the receiver.

When the last round is fired, the empty clip is ejected and the bolt is held open until a loaded clip is inserted, when it is automatically released and closed.

422. Machine Gun Mounts.—The weight of a machine gun and the forces resulting from automatic fire require the use of some form of strong, stable mount. It must permit the gun to be moved in elevation and azimuth, either freely under the control of the gunner's hands, arms, or body, or as constrained by mechanical devices. Essentially,

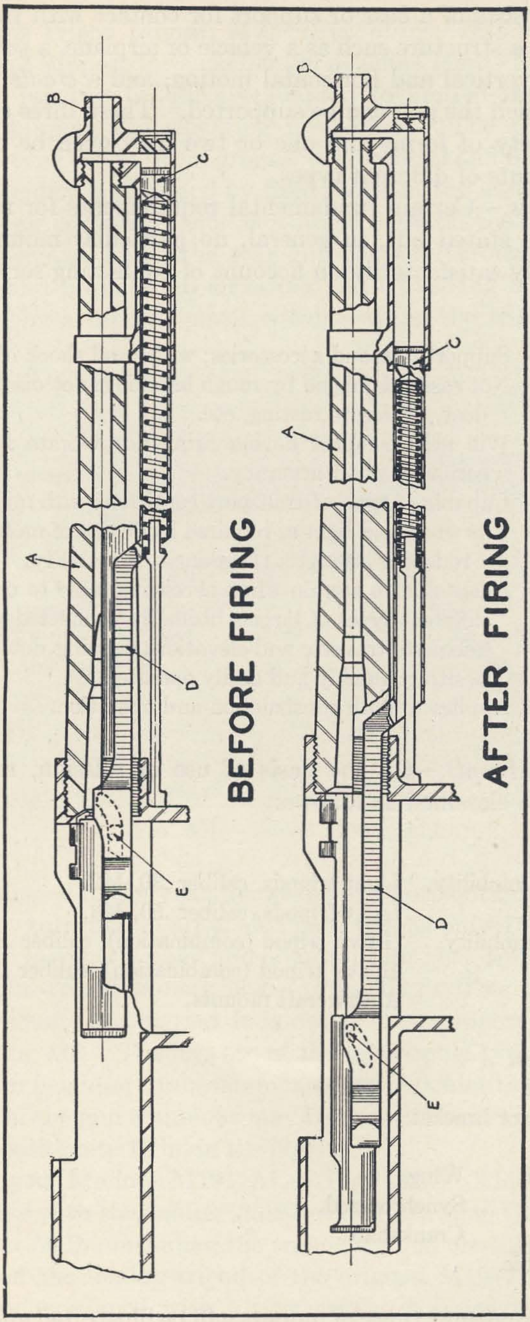


Fig. 360.

the mount consists of a *base* or support for contact with the ground or attachment to a structure such as a vehicle or airplane, a *yoke and pintle* for providing vertical and horizontal motion, and a *cradle* mounted on the yoke in which the gun can be supported. These three elements will assume a variety of forms and one or two may even be combined or missing in mounts of different types.

Requirements.—Certain fundamental requirements for machine gun mounts can be stated but, in general, no particular mount can meet them all equally satisfactorily on account of conflicting service requirements.

Strength —	Support gun and accessories; withstand shock of firing.
Ruggedness—	Not easily damaged by rough handling; not disabled by sand, dust, moderate rusting, etc.
Stability —	Will neither upset during firing nor vibrate sufficiently to seriously affect accuracy.
Mobility —	Capable of type of transport consistent with mission.
Weight — Size —	As small and light as required by degree of mobility, without reducing strength, ruggedness or stability.
Flexibility—	Adaptable to terrain when necessary; able to quickly engage different types of targets normally connected with mission; adequate traverse and elevation; training devices accurate, positive, quickly and easily operated.
Simplicity—	Applies to both construction and operation.

Classes of Mounts.—On the basis of use or mission, machine gun mounts may be classified as follows:

Ground.
- High mobility. Light tripods, caliber .30, M2.
  - Light tripods, caliber .50, M3.
- Low mobility. Heavy tripod (combination), caliber .30.
  - Heavy tripod (combination), caliber .50.
  - Antiaircraft mounts.

Vehicular.
- Turret.
- Fixed.
- Exterior bracket.

Aircraft.
- Fixed. Wing.
  - Synchronized.
  - Crankshaft.
- Flexible.

The more important types of mounts will be illustrated and discussed.

423. Light Tripod Mount, M2.—(Fig. 361.) This mount provides a light, strong support for a caliber .30 machine gun. It is designed for ground fire, but can be quickly adapted to limited-angle antiaircraft fire by unclamping the elevating mechanism. The tripod is of the fixed-height type ($9\frac{3}{4}$ in. from ground to trunnion) and has folding tubular legs. Rigidity is obtained by fixed stops on the legs and by the use of a traversing bar which acts as a brace between the rear legs. The traversing bar also forms the rear gun support through the elevating mechanism and provides an elevating and traversing base. The yoke is supported by a tapered pintle which seats in the tripod head. The

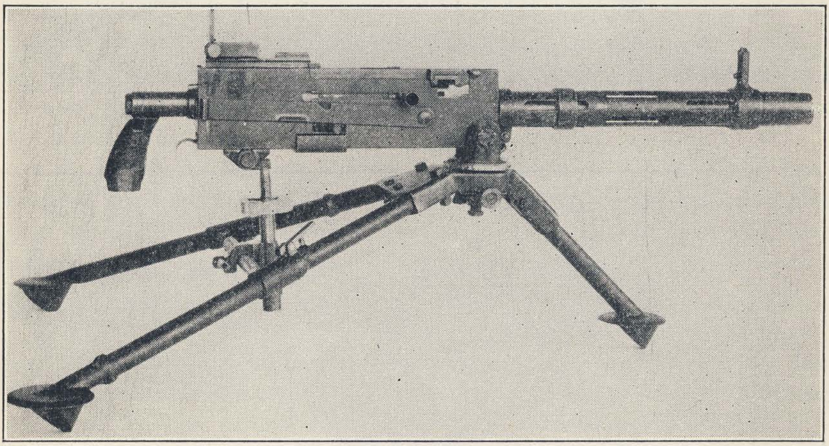


FIG. 361.—Tripod Mount, M2.

gun is trunnioned in the yoke by means of a horizontal bolt. The complete mount, carrying an air-cooled gun, weighs only $41\frac{1}{2}$ lb., so that it can easily be carried by hand and is suitable for pack transport.

424. Light Tripod Mount, M3.—(Fig. 362.) This is similar to the preceding mount, except that it is designed to support the caliber .50 Machine Gun, M2. The legs are of the telescoping type so as to adjust the mount for height or to accommodate it to irregularities of the ground. The height of the gun trunnions may be varied from 10 in. in the lowest, or normal, position to 13 in. in the highest.

425. Tripod Mount, M1917A1.—(Fig. 363.) This mount is designed for use with the caliber .30 Browning Machine Gun, M1917, and weighs about 50 lb., including the traversing and elevating mechanisms. It consists of the folding tripod of the original M1917 mount, slightly modified and equipped with a new cradle designed to meet modern combat conditions. For engaging terrestrial targets the mount may be

laid in elevation and direction by means of scales. Slow motion handwheels, equipped with 1-mil clicks, permit changes in both directions. The mount may be quickly freed for antiaircraft fire and for this pur-

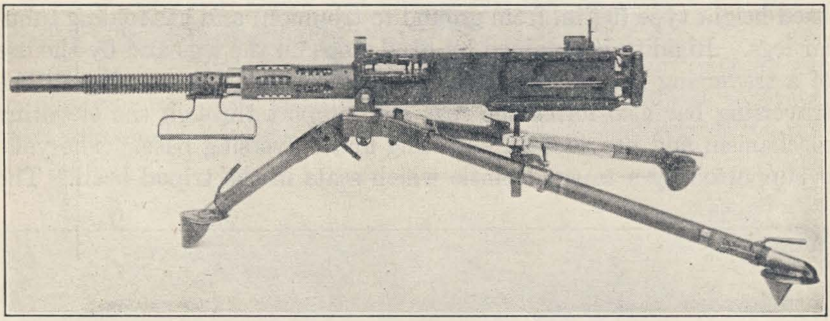


FIG. 362.—Tripod Mount, M3.

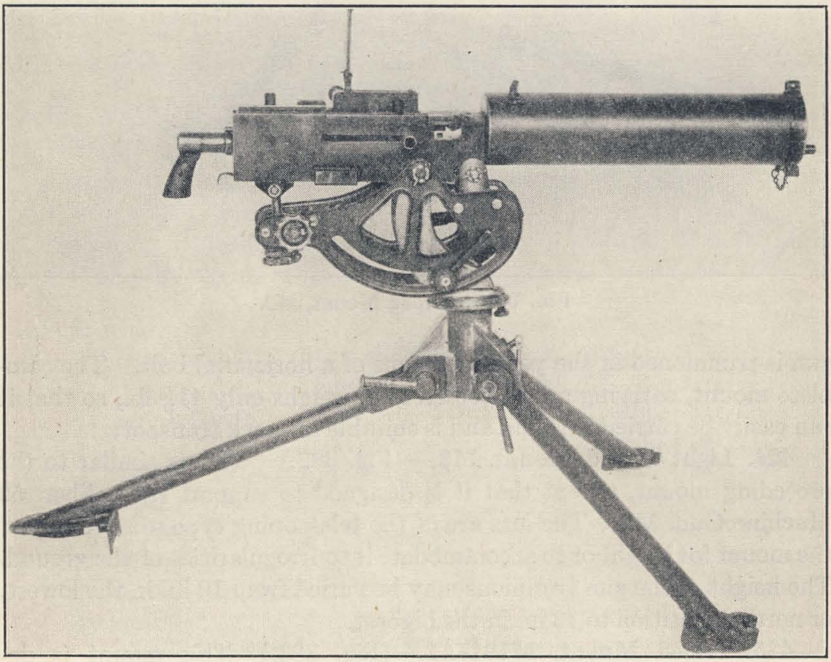


FIG. 363.—Tripod Mount, M1917A1.

pose is capable of 360° traverse and 65° elevation. Stability has been increased by raising the trunnions so that they are approximately on the resultant line of action of the recoiling parts.

A tripod having essentially the same characteristics, but of sufficient strength and stability to withstand the greater firing stresses, may be used to support the air-cooled caliber .50 Machine Gun, M2, when employed as a ground weapon.

426. Antiaircraft Tripod, M1.—This mount was designed for use with the caliber .50 Machine Gun, M1921, for antiaircraft fire. It is adapted for use with the caliber .30 Machine Gun, M1917, to secure ammunition economy in target practice. The cradle is mounted in trunnions on the yoke, which, in turn, is supported in the tripod socket by a pintle. The tripod legs are hinged and are provided with hinged braces to hold the tripod in the open position.

This mount has limited mobility by hand, since it weighs 255 lb. without the gun. The trunnions are 5.5 ft. from the ground to facilitate the following of aerial targets. The mount is free in elevation and traverse, and is controlled by the gunner's body through a combination shoulder and back rest.

427. Vehicular Mounts.—These include mounts for offensive missions, as in tanks and combat cars, and those which are intended primarily for local defense or emergency use, as on scout cars or trucks; for defense against low-flying airplanes, the latter should be suitable for antiaircraft fire.

Tanks and combat cars have hulls and superstructure made of armor plate to afford protection from enemy fire. At the same time, the vehicle is essentially a mobile firing platform, designed to carry the gun and its crew close enough to the target to deliver effective fire. It follows that the gun must be mounted in an opening in the armor and must have sufficient vertical and horizontal motion to permit laying on any normal target. The demand for protection imposes limitations which tend to restrict the field of fire provided.

The design of the mount is complicated by the requirement that it completely fill the opening in the armor to prevent entrance of bullets, lead splash, and shell fragments. The exposed parts must be strong enough to withstand impact of missiles, and to prevent functional or structural failure. Protection may be afforded by a shield of armor plate, mounted on the weapon or mount outside of the hull.

On certain armored vehicles the gun is mounted in a turret which may be revolved. (Fig. 364.) In this case, provision need only be made in the gun mount for traverse of a very few degrees; the limits of elevation must meet the range requirements and permit firing on targets below and above the height of the vehicle. The turret mount may support two machine guns, one of caliber .30 and the other of caliber .50. A single telescopic sight is provided, and the guns may be

fired separately or at the same time. A shoulder rest is provided for directing the mount.

If a rotating turret is not provided, or if the mount is supported in a hull wall, provision must be made in the mount itself for the traverse necessary to secure the desired field of fire, and to permit ready maneuvering in direction. This type usually mounts one gun only. The required horizontal and vertical movement may be attained by use of a

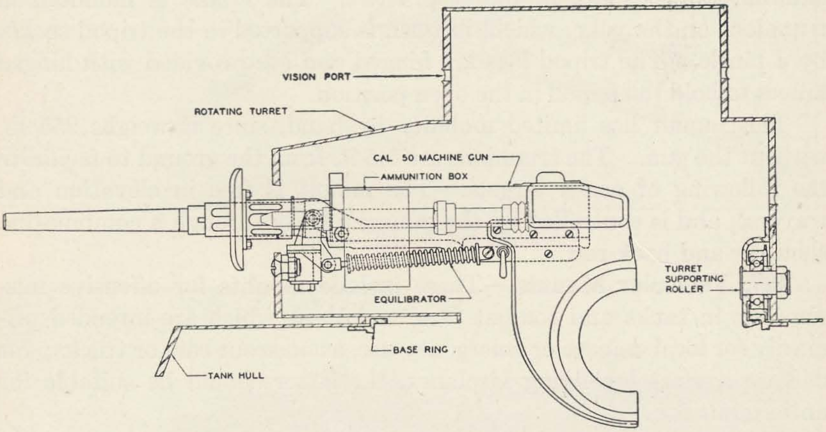


FIG. 364.—Typical Gun Mount in Tank Turret.

gimbal support, illustrated in Fig. 365, a ball and socket support, illustrated in Fig. 366, or by a combination of the two.

Certain combat vehicles may be provided with external brackets on which the guns are mounted, for both ground and antiaircraft defense. These are very simple mounts, consisting essentially of a supporting bracket or pedestal, in which is pintled a gun-supporting member which permits free elevation and traverse.

428. Aircraft Mounts.—Aircraft machine gun mounts are classified as fixed and flexible, depending upon whether the gun is fixed in direction so that it has to be aimed by directing the plane or can be aimed independently.

A fixed mount need only furnish support for the gun. This type is usually located in a wing, the landing gear, or the forward part of the fuselage, so that the gun is always pointing dead ahead. Provision must be made for remote control of the firing mechanism. These controls are usually either electrical, using solenoids with movable cores to operate the mechanisms, or mechanical, operated by a cable drive from some part of the engine such as the camshaft. The latter type, by use of cams, is so arranged that the machine gun can fire through the

propeller. A machine gun so operated is called "synchronized." Machine guns in fixed mounts are ordinarily fired by the pilot who controls the direction of fire by maneuvering the airplane.

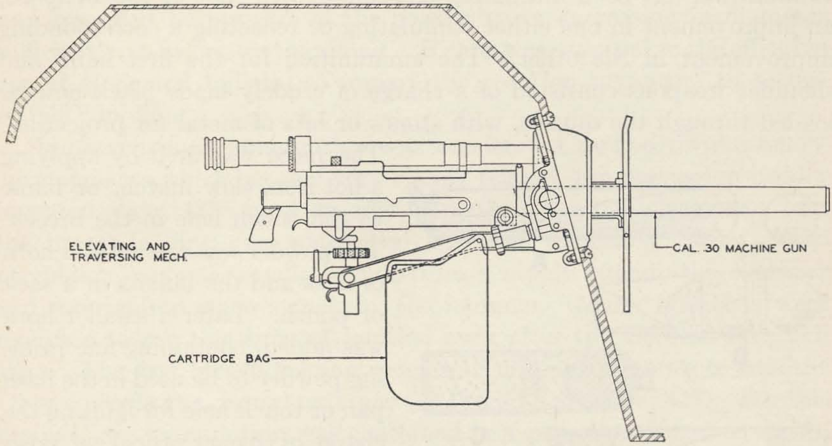


FIG. 365.—Section through Fixed Gun Mount.

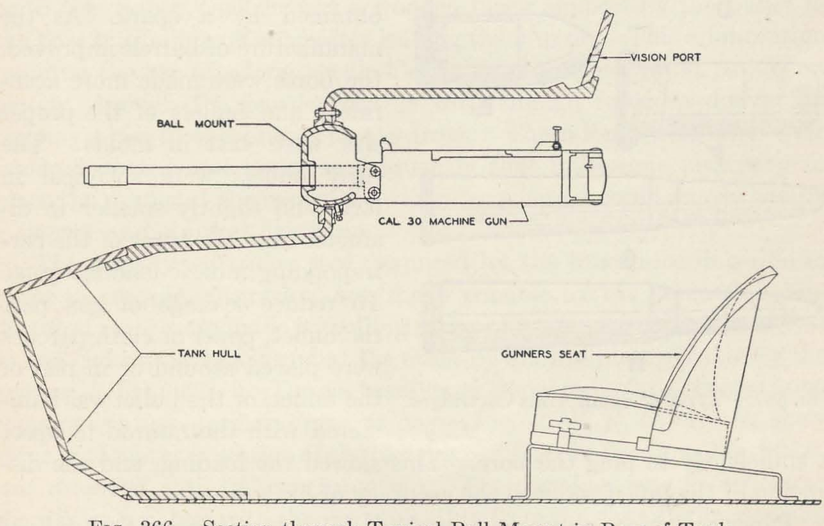


FIG. 366.—Section through Typical Ball Mount in Bow of Tank.

A flexible machine gun mount, sometimes called a "tourelle," provides 360° traverse on a base ring, elevation up to 90°, and as much depression as is permitted by interference of parts of the airplane. Each flexible mount requires the services of its own gunner and is usually placed in the rear part of the fuselage.

SMALL ARMS AMMUNITION

429. History of Development.—The development of small arms ammunition has been intimately associated with that of the weapons, an improvement in one either stimulating or reflecting a corresponding improvement in the other. The ammunition for the first hand and shoulder weapons consisted of a charge of crudely made black powder loaded through the muzzle, with stones or bits of metal for projectiles. The piece was fired by applying a hot iron, slow match, or flame to the touch hole in the breech. The powder was carried in a horn or flask and the bullets in a sack or pouch. Later a smaller horn was added, containing fine priming powder to be used in the flash pan or touch hole for igniting the charge of coarser propellent powder in the chamber; ignition was obtained by a spark. As the manufacture of barrels improved, the bores were made more accurately and bullets of the proper size were cast in molds. The early bullets were spherical in form and slightly smaller in diameter than the bores of the corresponding muzzle-loading guns. To reduce leakage of gas past the bullet, paper or cloth patches were placed around or in rear of the bullet, or the bullet was hammered with the ramrod to upset it sufficiently to plug the bore. This slowed the loading, and the distortion of the bullet reduced the accuracy of fire.

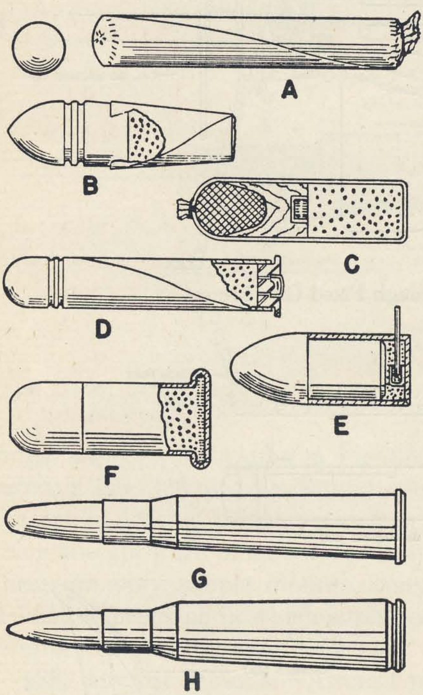


FIG. 367.—Types of Small Arms Cartridges.

Paper cartridges appeared as early as 1586, consisting at first only of separately-wrapped powder charges from which the powder could be poured into the barrel. (Fig. 367*A*.) In 1625, when Gustavus Adolphus adopted paper cartridges as standard in his army, the bullet had been included in the cartridge, and the whole unit was loaded into the weapon after tearing off the rear end of the wrapping to expose the powder to the igniting flame. (Similar to Fig. 367*C*.)

Later the bullet was elongated and the base made either flat or with a cone-shaped hollow. (Fig. 367*B*.) This gave better obturation and made possible the use of rifling in muzzle-loading guns. The bullet was small enough to be loaded from the muzzle; on firing, the thin base was expanded by pressure of the powder gases, increasing in diameter sufficiently to be cut by the rifling. Rifling was essential to the effective use of elongated bullets, to impart the rotation necessary to secure stability in flight.

Improvement in ammunition was accelerated by two revolutionary developments which became very closely related, the percussion primer invented about 1835 by Alexander Forsyth, a Scottish clergyman, and the breech-loading gun which had appeared somewhat earlier. The percussion cap was usually mounted on a nipple outside the chamber and was ignited when struck by the hammer. Many flintlocks were modified to use this type of ignition even after the close of our Civil War. The first breech loading weapon of military importance was the Dreyse needle gun, introduced into the Prussian army in 1848. For this weapon, the ammunition was contained in a paper cartridge, as shown in Fig. 367*C*, with the primer attached either to the base of the bullet or to the "sabot," which was a wooden block supporting the bullet in the bore but falling off soon after leaving the muzzle. This ammunition required the use of a long needle-like firing pin, which could pass completely through the powder charge with enough force to deliver an igniting blow to the primer at the front. These long firing pins were easily distorted and broke so frequently that it became necessary to place the primer at the rear of the cartridge where it could be reached by a shorter and sturdier firing pin.

The metallic cartridge case, required by the breech-loading rifle in order to provide obturation, was made possible by the percussion cap. The first cases were made by rolling strips of brass into cylinders, closed at one end by the bullet and at the other by an iron plate containing the primer. (Fig. 367*D*.) Drawn brass cases appeared soon after and have remained in use until the present day. Fig. 367*E*, *F*, *G*, and *H*, show steps in the later evolution of the cartridge. The pin-fire type, Fig. 367*E*, was provided with its own firing pin. The cartridge was loaded in to the rifle or revolver with the pin projecting from the chamber in position to be struck by the hammer. Rim fire cartridges, Fig. 367*F*, containing an annular ring of primer mixture in the rim formed at the base of the case, were used extensively at one time, and are still employed in caliber .22 and certain other cheap cartridges.

430. Modern Types.—The principal standard types and calibers of small arms ammunition used in our service are:

Caliber .22 ball, long rifle.
Caliber .45 ball.
Caliber .30 armor-piercing, ball, and tracer.
Caliber .50 armor-piercing, ball, and tracer.

In addition to these there are miscellaneous types, including dummy, blank, and high-pressure cartridges, used for training or testing.

431. Components of Complete Round.—The complete round consists of a cartridge case containing a percussion primer, a charge of smokeless powder, and a bullet. (Fig. 368.)

The Cartridge Case.—The brass case is made in one piece by several drawing and machining operations which give it the final shape and dimensions specified. It is annealed several times during manufacture to permit further drawing and to produce the desired physical qualities. The neck is annealed after the final draw to permit crimping against the bullet and to remove residual strains which would cause cracking in storage. The base contains the primer seat, vent hole, and extracting groove. The vent hole is for the passage of the primer flame to the propellent powder in the case. The rimless case is standard for our service ammunition (except caliber .22) in order to reduce the volume required for packing and storage, and to facilitate its use in automatic and semi-automatic weapons. The functions of the case are to assemble the primer, powder charge, and bullet in one weatherproof unit, to support them in their relative positions in the chamber, and to provide obturation during firing by expanding against the wall of the chamber, thus preventing escape of the powder gases to the rear. The body of the case is slightly tapered to permit easier extraction after expansion by the high gas pressure. The physical properties of the case must be such as to provide the necessary strength to withstand firing and extraction stresses. It must be sufficiently hard to prevent excessive resistance to extraction, and yet ductile enough to prevent transverse rupture when used in automatic weapons where the high rate of fire allows less time for reduction of pressure before the breech is open.

The front end of caliber .30 and caliber .50 cases is necked-down to form a cylindrical seat for the bullet; the mouth is crimped into a cannelure on the bullet to secure it in the proper position. The caliber .45 case is cannelured as illustrated in Fig. 368, to prevent the bullet being pushed beyond the correct depth.

The Primer.—The standard small arms primer is composed of a cup, percussion pellet, and anvil, assembled as a unit before insertion in the primer seat. In cartridges to be used in machine guns, the primer is crimped in the cartridge case to secure it.

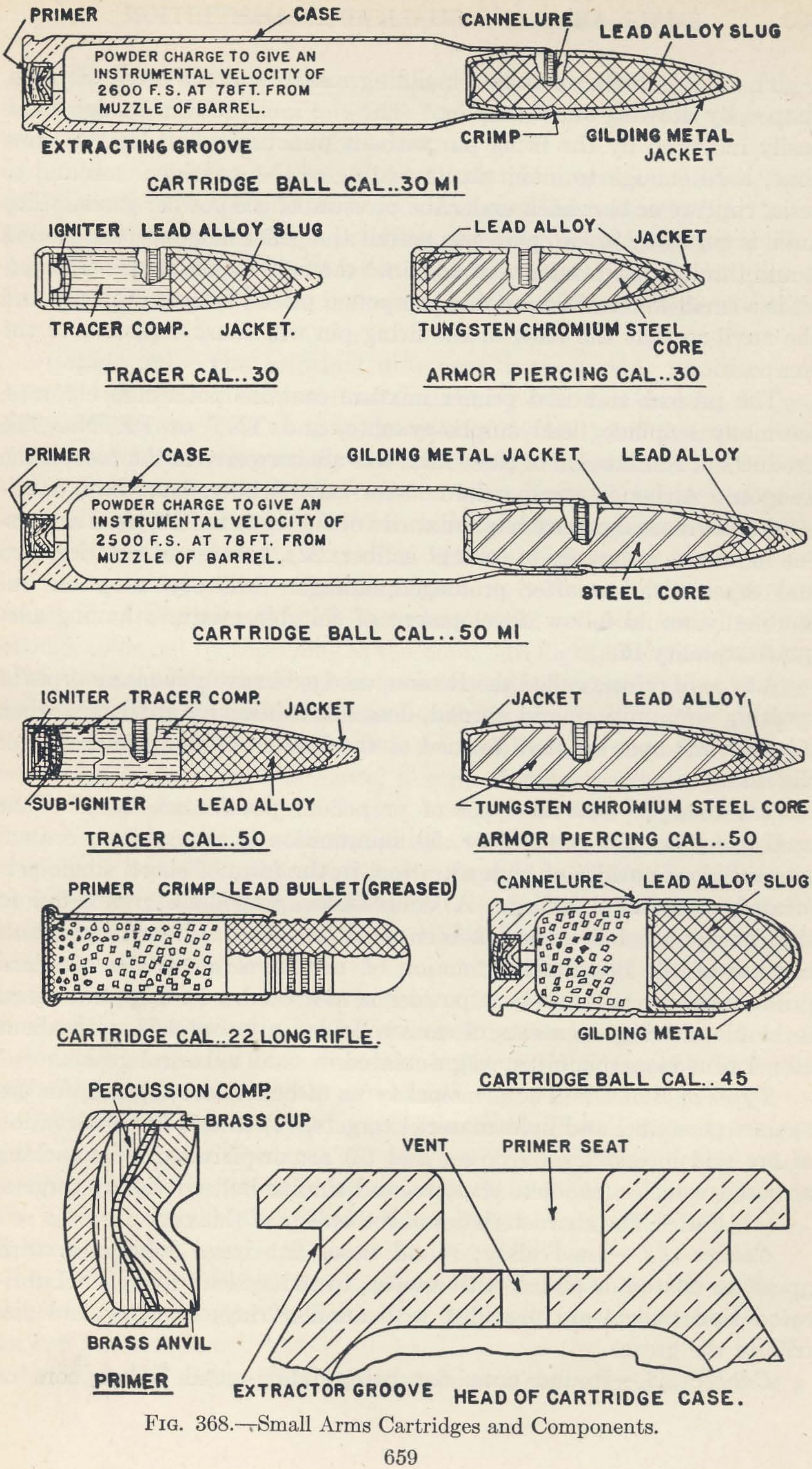


FIG. 368.—Small Arms Cartridges and Components.

The cup is made of brass or gilding metal, and the anvil of brass, shaped by drawing and stamping. The cup must be soft enough to be easily indented by the firing pin without puncturing but, at the same time, hard enough to maintain its seating in the cartridge case and to resist rupture or blowback under the pressure of the powder gases. The anvil is cut away in two places to permit the pellet flame to pass around it and through the primer vent hole into the body of the case. The pellet is a small wafer of detonating compound placed between the cup and the anvil so that the blow of the firing pin will cause explosion of the composition.

The present standard primer mixture contains potassium chlorate, antimony sulphide, lead sulpho-cyanate, and TNT or PETN. The products of combustion of these mixtures are corrosive in the bore of the weapon. Although commercial non-corrosive primers have been developed and are used extensively, mixtures of this type are not used at present in service ammunition (except caliber .22), because of deterioration and desensitization after prolonged storage. Military adoption undoubtedly would follow development of suitable mixtures having adequate stability life.

A type of primer called the *Berdan*, used extensively in many types of sporting ammunition, and abroad, does not contain an anvil but, when inserted, fits over an anvil formed at the bottom of the primer seat of the case.

The Charge.—Several types of propellent powder are used. That used in caliber .30 and caliber .50 ammunition is a graphited, coated, nitrocellulose powder of high nitration, in the form of short, single-perforated, cylindrical grains. A double-base propellant granulated in thin non-perforated discs has been used in caliber .45 cartridges, but, because of the desensitizing action of nitroglycerin on the standard primer mixture, a single-base powder is now used. E. C. powder used in blank cartridges consists of semi-colloided nitrocellulose with about 10 per cent inorganic nitrates, granulated in small spherical grains.

Types of Bullets.—The principal types of bullets are (1) ball, for use against personnel and light matériel targets, (2) tracer, for observation of fire and incendiary purposes, and (3) armor-piercing, for attacking armored vehicles, concrete shelters, and similar bullet-resisting targets.

(*a*) *Ball.*—The characteristics of the bullets of this type are:

Caliber .22.—Lead alloy; round nose, flat base; lubricated with grease or coated or plated with copper, to reduce lead fouling. Lubricated lead bullets are provided with annular rings to carry and distribute the grease.

Caliber .45.—Round nose, flat base, gilding-metal jacket, core of

lead hardened with antimony. Lead bullets (without jackets) have been tested and found satisfactory for use. They have no advantage over the jacketed type for service use.

Caliber .30.—Long ogive, 9° boat tail, gilding-metal jacket, lead-antimony core. A cannelure is provided near the "waist" of the bullet to act as a seat when the neck of the case is crimped in assembly, thus maintaining the longitudinal location of the bullet during handling and loading. The bullet jacket is closed at the base after the lead alloy core has been inserted.

Caliber .50.—The principal difference between this and the caliber .30 ball is the substitution of a relatively soft steel core for the lead alloy. This was done so that the caliber .50 ball and armor-piercing bullets would have essentially the same ballistic characteristics.

(*b*) *Armor-piercing Bullets.*—The bullet designed for armor penetration must be sufficiently hard to withstand the impact stresses without deformation; yet the maximum obtainable hardness must be lowered somewhat to avoid shattering due to brittleness. It must remain intact during penetration of the plate. The exterior must be soft enough to be cut by the rifling in the bore. In flight, the nose should be of the long slender ogival type to lessen retardation due to air resistance; for penetration, however, a blunter nose is required.

These conflicting requirements have been met by providing a bullet consisting of two essential parts, a core of tungsten-chromium alloy, shaped to give the best penetration, and heat-treated to produce optimum physical qualities, surrounded by a gilding-metal jacket shaped to obtain the best flight characteristics. Any space within the jacket not occupied by the steel core is filled with lead alloy, partly for ballistic balance and partly to increase the sectional density of the bullet. Tests have shown that the lead filler in the point of the bullet also aids penetration, especially at oblique impact. In assembling armor-piercing ammunition great care must be exercised to insure that the core and jacket will be co-axial; otherwise the bullet will not be stable in flight, with resulting loss of accuracy as well as velocity and striking energy.

As shown in Fig. 368, the base of the core is given a slight boat tail; this has been found to reduce the number of cores broken during penetration, caused by the base striking against the plate while entering. The core is cannelured to provide room for the metal displaced in producing the jacket cannelure.

Armor-piercing bullets are standard in calibers .30 and .50 and can be used in any weapon of either caliber designed to use the corresponding ball ammunition.

(*c*) *Tracer Bullets.*—This bullet contains a compressed column of a

pyrotechnic mixture which will give a bright flame when ignited by the burning of the propelling charge. The tracer composition is a mixture of materials, including (1) a fuel, (2) an oxygen carrier, (3) a color intensifier, and (4) binding and waterproofing agents. At present the standard color is red, although green has been used extensively in the past. Owing to the fact that the tracer flame is quite hot and not easily extinguished, tracer ammunition may be used for incendiary missions and has removed the necessity for providing special ammunition for that purpose.

Ordinarily, tracer is mixed with ball ammunition for use in order to locate the trajectory with reference to the target. Since the tracer trajectory is different from the ball trajectory, it is necessary to design the tracer ammunition so that its trajectory will give approximately the same point of impact as that of the ball up to some definite range. For caliber .30 this range is 600 yd. and for caliber .50 it is 1000 yd. The length of trace (distance traveled during burning) is about 850 yd. for caliber .30 and slightly over 1700 yd. for caliber .50.

The tracer jacket is similar to that used for ball, but must be somewhat thicker to withstand the high pressure exerted on the tracer mixture during the loading operation. This loading pressure is necessary to provide sufficient mass of the mixture for the time of burning desired, to produce the density required for certainty of burning, and to control the rate of burning. The base portion of the tracer element is known as the igniter; its composition is such as to insure ignition at the temperature developed by the propelling charge.

The tracer bullet has a flat base to provide the requisite exit orifice for the tracer flame. This flame is practically invisible from the front or side but can be seen readily from the rear, even in bright sunlight, because of its extreme brilliance.

432. Specifications and Tests.—The shape, dimensions, and other data pertaining to the complete round and its components have been determined by extensive investigation and experiment so as to insure the desired ballistic qualities in a cartridge which will also meet the requirements of manufacture, storage, and operation in all standard service weapons of the same caliber. These physical and ballistic requirements are published as the specifications covering manufacture and acceptance. Each lot of ammunition accepted must meet these specifications with sufficient uniformity to give satisfactory operation and the expected ballistic results in all the appropriate weapons. It is therefore necessary, first, to exercise rigid control over the manufacture of the cartridges and, second, to subject the finished ammunition to extensive tests in order to insure that all requirements have been met.

These requirements and the related tests may be divided into three classes: physical, ballistic, and functional. Physical requirements include dimensions and weights of all components and physical properties of all metals. Ballistic requirements are essentially based on velocity, accuracy, and pressure, as well as uniformity and certainty of ignition, as demonstrated in firing tests. Functional requirements relate to performance in the weapons for which designed.

A "lot" of small arms ammunition may vary from 200,000 to 1,000,000 rounds, all assembled by a single manufacturer, from uniform lots of components, and under uniform conditions. To test every cartridge is manifestly impracticable. It is standard practice to select from each lot a random sample, the tests of which are assumed to be representative of the entire lot. This sample contains approximately 1 per cent of the cartridges in the lot. The principal tests to which it is subjected will not only disclose whether the lot meets the general requirements for acceptance but will also indicate the particular types of weapons for which it is especially suited.

433. Physical Tests.—These include, among others, the following:

Gaging.—All components are gaged during manufacture and must be within prescribed limits. The acceptance test of the assembled cartridges is concerned only with those dimensions which affect operation in service weapons. For example, the overall length affects feeding and determines the seating of the bullet in the bore; the length of the case will interfere with closing and locking the breech if too long or, if too short, will prevent proper support in firing (excessive headspace) and may prevent the proper blow by the firing pin. The critical dimensions are checked by "go" and "no go" gages.

Visual inspection consists of thorough visual examination of the entire lot to detect physical defects in the cartridge cases, such as cracks, folds, bulges, deep draw scratches, etc., missing or inverted primers, and any other evidence of defects which might result in malfunctioning or accident.

The *mercury cracking* test is an accelerated aging test to determine whether the cartridge case may be expected to develop season cracks or splits after prolonged storage and aging. Such cracks result from manufacturing or assembly stresses and may be prevented, or the tendency to crack reduced by proper final anneal of the neck. Any potential crack due to residual stresses will develop quickly when cartridges which have been pickled in nitric acid are immersed for a few minutes in an aqueous solution of mercurous nitrate and nitric acid.

434. Ballistic Tests.—Tests to determine ballistic qualities are usually conducted in special standard weapons which are calibrated

periodically by firings with a standard lot of ammunition. During all acceptance firing tests, visual examination is made of all fired cases to detect ruptures, splits, pierced or leaky primers, and other visible defects, and record is made of all misfires, hangfires, failures to extract, and other malfunctioning.

Velocity Test.—A series of 20 to 40 rounds is fired to determine the expected average velocity of the lot under standard conditions. For acceptance, the sample must give the prescribed average muzzle velocity, with variations within prescribed limits.

Water Test.—Cartridges which have been immersed in water for at least 24 hours prior to firing are alternated with cartridges in the regular velocity test. Since moisture in the primer or propelling charge will result in lowered velocity, this test gives a direct comparison which will indicate whether the waterproofing of the cartridges is effective.

Pressure Test.—The pressures of a series of rounds are measured to determine the average pressure of the lot. The apparatus used is described in Chapter III. For acceptance, the required velocity must be attained within prescribed pressure limits. Since variations in pressures will normally be reflected by variations in velocity, velocities of pressure rounds are recorded as a check.

Accuracy.—This test, to measure the dispersion of the ammunition, is made in a special weapon called a Mann barrel. An ordinary receiver is mounted on an extremely heavy barrel which is free to slide on integral bearing rings in a V-shaped block. This weapon is designed to eliminate practically all the dispersion not due to the ammunition itself. The cartridges are fired in groups of ten at plain paper targets, located at a range of 50 yd. for caliber .45, and 600 yd. for calibers .30 and .50. Each target is measured to determine its statistical dimensions, such as center of impact, mean radius, and extreme and mean horizontal and vertical dispersions.

An additional accuracy test for tracer ammunition is to determine the locations on targets of the centers of impact of the tracer bullets relative to those of ball cartridges which have been fired alternately with the same weapon and laying. This is done at 600 yd. for caliber .30 and at 1000 yd. for caliber .50 ammunition.

Special Ballistic Tests.—A sample of each lot of armor-piercing cartridges is fired at standard armor plate to determine the penetrating capacity of the bullets and the physical characteristics of the cores as demonstrated by their action against the armor. Acceptance is based upon fulfillment of performance specifications, provided that the requirements of the preceding tests have been met.

Tracer ammunition is tested to determine malfunctions and length

of visible trace. Malfunctions such as muzzle burst, short trace, and non-trace are observed from the firing point. The length of trace is measured by down-range observers who determine the limit of burning of each round by reference to stakes spaced at known distances from the firing point.

435. Functional Tests.—Each lot of ammunition must be fired in each service weapon designed for its use, to observe its effect on their operation. In some of these tests it is necessary to use old or worn weapons as well as new ones, so as to approximate service conditions.

436. Grading of Small Arms Ammunition.—Regardless of the weapon in which it is to be used, all lots of a given type of ammunition must meet the same requirements for velocity, pressure, and accuracy. However, each lot of caliber .30 and .50 ammunition is given a grade designation to indicate the particular service weapon for which it is best suited. The grade symbols, uses, and certain factors responsible for the designation, are as follows:

AC: For aircraft machine guns. Based on selected uniformity in dimensions and weight, and minimum variation in primer action and ignition, in order to minimize malfunctioning when used in synchronized or remote-controlled aircraft weapons.

R (Refers to caliber .30 ammunition only): For use in rifles and automatic rifles. Based on low extraction effort and other factors.

MG: For use in ground machine guns only. Includes all lots not graded AC or R. Less stringent test limits are required because of the heavy construction of the weapon and the direct control exercised by the operator.

After long-continued storage, tests may disclose characteristics which impair the efficiency of a lot for use in the weapon intended. Regrading is then necessary. Normally it will be regraded MG for use in ground machine guns if still serviceable; if unserviceable and not to be used for any purpose, it is placed in grade 3 for subsequent salvage.

A list of all ammunition lots and their grade designations is published to the service to insure use in the proper weapons.

437. Packing, Marking, and Identification.—Small arms ammunition is issued in standard sealed and metal-lined packing boxes. Within, the ammunition is packed in cartons, in clips and cartons, in clips and bandoleers, or in machine gun belts, according to type and caliber, original grade designation, and use.

Information as to type, caliber, ammunition lot number, and the manufacturer is essential to the identification of small arms ammunition; this, with a knowledge of the grade to which currently assigned, is necessary to insure use in the proper weapon and for the proper pur-

pose. All essential information, except the grade symbols, is clearly marked on the outside of all packing cases, on identification cards within, on the carton labels, and on cards inserted in the bandoleers.

438. Developments and Trends.—As with all other ordnance matériel, the development of small arms ammunition is continuing in an effort to accomplish improvements required by modern warfare. For example, the necessity for further developmental effort to secure suitable non-corrosive primer mixtures, with adequate stability life, has already been mentioned.

Another development has been armor-piercing tracer. The tail of the caliber .50 A.P. core has been removed to provide space for a small tracer element which will burn long enough for the gunner to spot his shots with reference to the target.

A caliber .45 tracer has been produced for use in automatic pistols and Thompson submachine guns for signaling purposes. The large area of the tracer column permits a large, brilliant flame which may be observed for some distance in any direction when the bullet has been fired vertically.

The greatest progress of the last few years has been in the direction of increased velocity. The increasing use of high-speed aircraft and armored vehicles has created a demand for ultra-high velocities. This demand has been based upon the desire to keep the time of flight as low as possible, so as to simplify fire control problems and, in the case of armored targets, the need for high remaining velocities in order to insure penetration at normal battle ranges and to increase the maximum range at which penetration may be expected. The extreme velocity demand has not yet been met in standard service weapons, although it may be met by means of special weapons.

CHAPTER XVIII

LIGHT ARMOR

439. General.—The term light armor applies to protective armor plate $1\frac{1}{2}$ in. or less in thickness. Its principal military use is on armored combat vehicles such as tanks, combat cars, and armored cars, to furnish partial protection to the operating personnel, and to vital parts and mechanisms, against small arms bullets, intermediate caliber projectiles, and shell fragments. Light armor is employed also, but in less quantities, in the fabrication of gun shields used on certain types of mobile artillery, and for other special purposes such as the manufacture of helmets. Its use on aircraft has been suggested to protect such vital parts as gasoline tanks. The degree of protection afforded depends upon the type of armor, its physical qualities, and the thickness of the plate employed.

440. Types.—There are three general types of light armor used on combat vehicles, as follows:

Face-hardened plate, which has been so fabricated and heat-treated that the face exposed to fire is given a specially hard and compact texture and the remainder of the plate made strong and tough,

Homogeneous plate, which has the same chemical and physical characteristics throughout, and

Armor castings, which are castings made of high alloy steel and so heat-treated as to have the properties of armor plate. Such castings may be either of the homogeneous or face-hardened type.

441. Physical Properties; Characteristics of Types.—The physical qualities of primary importance in determining the general suitability of light armor are

Hardness, to turn or to defeat the projectile,
Toughness, to resist cracking or shattering due to impact,
Ductility, to prevent spalls, buttons, or slivers being thrown from the back, and
Strength, to withstand the stresses to which the assembled structure will be subjected in service.

Although there is more or less incompatibility between certain of these

properties, for example between hardness and toughness and between ductility and strength, the desired properties can be obtained, within limits, by proper selection of alloy steel, suitable working and fabrication, and appropriate heat treatment.

The properties and characteristics of the several classes of light armor are:

Homogeneous Plate.—This class of armor is consistently hard throughout, some sacrifice of toughness and ductility being necessary to obtain the degree of hardness desired. This plate has some tendency to shatter under repeated impact, and also to spall; in the thinner gages it offers less resistance to bullets than face-hardened plate. Homogeneous plate, however, is cheaper, quantity production could be obtained more readily in time of war, and the simple heat treatment employed produces relatively few manufacturing losses due to shrinking and warping. It is especially suitable for thick plates and those having an irregular outline or containing a large number of fabricated apertures. From a service standpoint, the ability to employ welding to a very limited extent and to perform field repairs not possible with face-hardened plate is advantageous.

Face-hardened Plate.—In this class of plate, the hardness and the resistance offered to the bullet is greater on the front face than in the homogeneous type, and this permits a lower degree of hardness through the remainder of the plate, which can thus be made very tough and ductile. It stands up well under repeated impacts, has considerable structural strength, and in very thin sections has a higher resistance to penetration than homogeneous plate. It offers the most protection per pound of metal. However, it is very expensive to manufacture. The metallurgical problem of securing the proper chemical compositions in the plate metal and in the case is a difficult one, and the heat treatment required is quite complicated. Manufacturing losses due to shrinkage and cracking during quenching are high. The best results are secured when produced in small lots.

Armor Castings.—Castings are used to a limited extent where complicated shapes are required, such as a combined support and protection for small irregularly shaped mechanisms. Homogeneous castings of proper chemical composition and appropriate heat treatment have qualities that compare favorably with rolled plate. Face hardening of castings has been done experimentally.

442. Chemical Composition and Heat Treatment.—The effectiveness of armor plate depends basically upon its chemical composition, which must be such that the required physical qualities will be produced by appropriate heat treatment. The precise composition and heat

treatment employed by the various manufacturers differ considerably. Typical alloys employed include chrome-molybdenum-vanadium, nickel-molybdenum, nickel-chrome-molybdenum, and nickel-tungsten.

The steels used for the several types of plate are quite similar in composition except that a lower carbon content is employed in those to be carburized for face-hardened plate. The following is an outline of typical heat treatment processes:

Homogeneous Plate.—Quench in oil from about 1600° F. and draw at about 1125° F., with resulting hardness of about 425 Brinell. Oil is employed as the quenching medium because it produces less distortion and less residual stress.

Armor Castings.—The process is similar to the above except that a high temperature anneal is necessary before the hardening operation.

Face-hardened Plate.—The face is first carburized, then the plate is quenched from about 1700° F. to refine the core, and requenched from about 1500° F. to refine the case. It is then drawn at about 700° F. The resulting face hardness will average over 500 Brinell, and that of the core about 375 Brinell.

443. Procurement.—The chemical composition of the steel, its heat treatment, and the methods of fabrication are left to the discretion of the manufacturer, who may supply either homogeneous or face-hardened plate as he elects. The specifications prescribe only that the plate furnished shall be of such chemical composition, heat treatment, fabrication, hardness, and uniformity as will enable it to pass the prescribed firing tests to determine toughness, ductility, resistance to penetration, and resistance to shock.

Acceptance is based solely upon the results of tests of sample plates conducted at the Proving Ground. For each thickness of plate and from each production lot the contractor furnishes one 36 in. by 36 in. primary sample for shock test, and one finished, fabricated plate for ballistic test. Failure of any sample to pass any of the tests results in rejection of the lot it represents.

444. Tests.—Plates are mounted for test on a rigid frame and firings are conducted at a range of 100 yd., the powder charges being adjusted as necessary to obtain the specified impact velocities.

Shock plates are subjected to 25 hits, full automatic machine-gun fire, using caliber .30 armor-piercing ammunition for plates to include $\frac{3}{8}$ in. thickness and caliber .50 armor-piercing ammunition for plates above $\frac{3}{8}$ in. and including $\frac{5}{8}$ in. Plates above $\frac{5}{8}$ in. and including 1 in. are subjected to at least two hits by 37-mm. A. P. solid shot striking not less than 6 in. nor more than 15 in. apart. In each case, lack of toughness, as indicated by cracks during the test or within 24 hours thereafter,

and lack of ductility, as evidenced by crumbling, spalls, buttons, slivers, or lack of clean smooth entrance hole and exit, will cause rejection.

For determination of resistance to penetration, plates to include 0.50 in. are tested with caliber .30 A. P. ammunition and thicker plates, to include 1 in., with caliber .50 A. P. ammunition. Each thickness of plate must resist complete penetration of at least three rounds of armor-piercing ammunition of the specified caliber, at or above the specified velocity of impact. These velocities vary in caliber .30 firings from 1650 f. s. for the $\frac{1}{4}$ in. plate to 2250 f. s. for the $\frac{1}{2}$ in. plate, and in caliber .50 firings from 1890 f. s. for $\frac{9}{16}$ in. plate to 2450 f. s. for 1 in. plate. In addition, $\frac{1}{4}$ in. and $\frac{5}{16}$ in. plate must resist complete penetration by caliber .30 ball ammunition at 50 yd. range and normal velocity. Complete penetration occurs when any portion of the bullet projects through the plate or when any hole is produced sufficient to admit the passage of light.

445. Penetration of Armor.—The most important factor affecting penetration of armor plate is bullet or projectile energy. From the expression for kinetic energy, $\frac{1}{2}MV^2$, in which M is the mass of the bullet and V its striking velocity, it is evident that the velocity factor is of far greater significance than mass. Striking energy, expressed in foot-pounds, is usually obtained from a modification of the above formula as follows:

$$E = \frac{WV^2}{2 \times 7000g}$$

in which W is the weight of the bullet in grains, V its velocity in feet per second, and g the acceleration due to gravity.

The velocity factor is of such importance that, if very high striking velocities are obtained, penetration is little affected by the material of which the projectile is composed, and ball ammunition or other comparatively soft bullets will penetrate as readily as standard armor-piercing ammunition at slightly lower velocities. One hypothesis advanced to account for this phenomenon considers the critical velocity as that velocity at which the impact of the projectile sets up a shearing stress exceeding the strength of the plate material in shear. The action of the bullet is thus similar to that of a punch in a high-speed punch press.

The penetration of a projectile in armor is computed by means of various empirical formulas. The most useful application of such a formula is to obtain a coefficient or factor K, referred to as the De Marre coefficient, which permits comparison of the resistance of plates of the same general type but of varying thicknesses, using ammunition of the

same type and penetrative ability. The formula for determination of the De Marre coefficient takes into account the diameter of the projectile, the thickness of the armor plate, and the particular velocity, designated as the *ballistic limit* and determined by test, at which the plate will just resist complete penetration by the projectile in question.

Using standard caliber .30 and caliber .50 A. P. ammunition, the De Marre coefficients have been determined for various thicknesses of standard homogeneous and face-hardened plates by means of the following formulas:

$$\text{For caliber .30} \qquad K^2 = \frac{\text{B.L.}}{2945\sqrt{t^3}}$$

$$\text{For caliber .50} \qquad K^2 = \frac{\text{B.L.}}{6320\sqrt{t^3}}$$

in which B. L. is the ballistic limit of the plate in feet per second, and t the thickness in inches. These expressions hold only for the 168-grain and 752-grain standard A. P. bullets; similar formulas may be determined for other calibers and other bullets.

Comparison of various plates can be made by determining their ballistic limits by firings, and comparing the values of K computed from the above formulas with standard or prescribed values. Also, the armor-penetrating capacity of various types of small arms bullets can be compared by determining the striking velocities required for complete penetration of the same plate or plates for which K is known.

Other things being equal, the penetration of a projectile in armor depends upon the striking angle, being greatest at normal impact. Up to angles of 20° from the normal, the amount of penetration is but little affected; beyond 45° from the normal, little penetration is secured at ordinary striking velocities and ricochets may be expected. A rough rule is that the depth of penetration is proportional to the cosine of the angle of impact, measured from the normal. At very high striking velocities, penetration may be obtained at angles considerably greater than 45°.

In general, a plate will fail at lower velocities when struck by bursts from full automatic fire than it will from single shots. This is due to attrition and cumulative vibratory stresses. Complete penetration of the entire projectile is not essential for it to have effect. Even if very small openings only are made in the back of the plate, the lead splash entering from ball ammunition may be sufficient to incapacitate personnel.

446. Armor-piercing Bullets.—Except at extremely high velocities, the following factors are of greatest importance in securing effective armor-piercing bullets: hardness of core; form; stability.

Hardness of Core.—The core must be of sufficient hardness to enable it to penetrate the plate at the desired striking velocity, and without shattering or appreciable deformation. The most satisfactory material is a 3 per cent tungsten steel, specially heat-treated so that the point and front portion will be sufficiently hard to penetrate the plate, and the body or rear portion strong and tough enough to resist deformation.

Form.—The most effective shape for the point of the core depends upon the type of plate and angle of impact. A long sharp point is more effective against comparatively soft plate at normal angles of impact, but is not so effective against hard plate, or at angles greater than 20° from the normal. In our service, a shorter and less sharp point is employed than that used by certain other armies because of its greater effectiveness under the usual conditions to be expected, that is, against comparatively hard plate and angles of impact varying considerably from the normal.

Stability.—The *yaw* of the bullet greatly affects its penetration in armor. A very small amount of yaw, too small to show up in firings through a paper screen, will reduce materially the bullet's penetrating capacity, and as the amount increases the effect increases more rapidly. If the bullet is approaching zero yaw as it strikes the plate, the effect will be greatly diminished, but if it has just passed through zero yaw as it strikes, the effect is increased and little penetration will be secured.

447. High-velocity Bullets.—The importance of the velocity factor in armor penetration is apparent, and increasing the velocity of a projectile offers a simple way of increasing its kinetic energy. It should be noted, however, that the increase in velocity and energy at the muzzle of the weapon is not maintained, since the retardation due to air resistance increases with the velocity of the bullet. Hence, the greater the initial velocity, the greater will be the rate of velocity loss. Further, most special bullets designed to attain very high muzzle velocities have low sectional densities, with less mass than standard bullets of the same caliber, and this factor also increases the retardation due to air resistance, and the rate of loss of velocity. For example, a 48-grain caliber .22 bullet with a muzzle velocity of 4000 f.s. will lose about 900 f.s. velocity and one-third of its energy in the first 100 yd. of its flight.

On the other hand, increase in mass of the projectile is effective throughout its flight, and with the same striking velocity a small but consistent increase in penetration can be obtained at any range. Also, by increasing the sectional density of the projectile, or the value of w/d^2

in the expression for the ballistic coefficient C, its capacity to overcome the resistance of the air is increased, and its rate of velocity loss during flight is decreased. For example, a 1-lb. 25-mm. projectile, with a muzzle velocity of 3000 f.s., will lose only approximately 160 f.s. velocity and 10 per cent of its energy in the first 100 yd. of its flight.

A number of experimental high-velocity bullets have been developed that displayed excellent characteristics at short ranges. It is probable, however, that very little improvement in armor penetration over that attained by standard bullets of conventional type has been obtained at ranges greater than 400 yd.

448. Armor Plate Structures.—The designer of a mobile armor-plate structure has three factors to consider, as follows: weight limits, degree of protection desired, and cost. All of these are interrelated and must be considered in the selection of each plate to be used.

Weight.—The weight of armor depends upon the thickness of the plate and the area covered. A plate 1 in. thick weighs 40 lb. per sq. ft. The total weight of armor provided for a combat vehicle such as a tank is limited by the basic tank design, and specifically by the capacity of the power plant. The required speed, acceleration, and load characteristics must be met. The remaining power is available for the transportation of armor. Limitation of weight thus limits the armor thickness and the degree of protection obtainable.

Protection.—All protection is partial but certain parts of the structure are considered vital as, for example, the driver's compartment of a tank. Such parts or areas must be furnished with more complete protection at the expense of others which are less vital. To afford the maximum protection would require the exclusive use of face-hardened plate, but in the application of this principle the increased cost of face-hardened plate and difficulties in manufacture and fabrication must be considered. It is often possible to use homogeneous plate on surfaces relatively unexposed to small arms fire, without much sacrifice in protection but with considerable saving in cost. This is also true of plates over $\frac{5}{8}$ in. in thickness.

Cost.—The cost of armor plate is affected by structural design. The losses incident to manufacture must be included in the estimated cost of the finished plate. These losses are influenced by design. Curved plates, particularly those having apertures in the curved surface, are very difficult to manufacture. Losses during heat treatment may run as high as 50 per cent in early stages of manufacture. Plates of extremely irregular shape should be avoided as far as possible and the number of apertures and accurate dimensions per plate kept to a minimum, if cost is to be kept low.

Assembly.—Two methods of assembly have been used, welding and riveting. Riveting was the original method; but, when welding technique and welding materials improved to such an extent that satisfactory mechanical strength was produced at the joints, welded construction was attempted. Welding, however, continued to produce difficulties which may be summarized as follows:

a. Lack of bullet resistance in the welds, and in the heat-affected zone adjacent thereto.

b. Cracking in and adjacent to the weld.

Individual plates can be welded in the annealed condition and then heat-treated with satisfactory results, but destructive stresses result from heat treatment when this method is applied to complex structures.

Present standard practice calls for riveted construction throughout. Casting is employed for very complicated structures, such castings being subsequently riveted to the vehicular plate to form the required shape. The castings show ballistic properties comparable with those of rolled homogeneous plate, but not equal to those of rolled face-hardened plate. They have the advantage over a welded unit of the same strength in that heat treatment is possible.

According to current practice, light tanks are provided with $\frac{5}{8}$-in. turret and front armor, $\frac{1}{2}$-in. on sides, and $\frac{1}{4}$-in. on top, bottom, and rear. The front, side, and rear armor is face-hardened and the top and bottom armor is homogeneous. The present tendency is toward the substitution of high tensile alloy structural steel for part of the $\frac{1}{4}$-in. homogeneous armor. The front plate is inclined at an acute angle with the horizontal in order to increase resistance to penetration. However, terrain variations and resulting angles of impact may readily neutralize this advantage. A large section of the front, containing a complicated gun mount, is cast in one piece of such a thickness as to approximate the resistance of $\frac{5}{8}$-in. armor. Medium and heavier tanks, which are slower moving and in which weight considerations are less important, are fitted with much thicker plate designed to withstand heavier projectiles and higher impact velocities.

CHAPTER XIX

AUTOMOTIVE EQUIPMENT

449. Classification and Types.—The term *motorization*, as used in the United States Army, refers to the replacement of animal transport by motor transport, and implies utilization of motor vehicles for the transportation of personnel and supplies, and for towing purposes, but not for actual combat. *Mechanization*, however, applies specifically to the adaptation and utilization of motor vehicular equipment for combat.

In general, military vehicles are classified as *transport* vehicles, and *combat* vehicles. The latter are designed primarily for combat purposes, and are equipped usually with armament and protective armor; they comprise the primary offensive weapons of mechanized troops, and suitable types are included in the organic equipment of other units for the performance of reconnaissance and other missions.

Motor vehicles may be classified by type according to character of traction as

- Full track vehicles,
- Convertible (wheel and track) vehicles,
- Half track vehicles, and
- Wheeled vehicles, which may be either
    - Two-wheel drive, or
    - Multiwheel drive.

It may be stated that, in general, all vehicles employed in the combat zone of the theatre of operations should combine standard road speed and performance with cross-country ability; that is, they should have both *strategic* mobility and *tactical* mobility. The degree to which these (generally) conflicting requirements must be met depends upon the military function and assignment of the vehicle. This, together with the practical difficulties of combining these requirements in a single vehicle, and the necessity of utilizing standard commercial types so far as practicable, has resulted in the adoption for military use of the several types listed above.

The full track-laying vehicle has the greatest off-road maneuverability, and experience has demonstrated that tracks are essential to attain

full battlefield mobility. Commercial track-laying vehicles fail to meet military requirements for speed, general road performance, and other essentials, and it has been necessary to develop special types for military use. The special convertible vehicle attempts to solve the mobility problems by provision of means for off-road operation on tracks and on-road operation on wheels. The half-track vehicle is essentially a modification of commercial wheeled vehicles by substitution of a short track-laying unit for the rear wheels. In relative off-road mobility, this vehicle ranks between the full track-laying and the wheeled types.

Wheeled vehicles of several types are available, including 4-wheel with 2-wheel drive or 4-wheel drive, and 6-wheel with 4-wheel or 6-wheel drive. They meet all requirements as to road performance, but are deficient in varying degrees for off-road use. It is to be noted that cross-country ability increases with the number of wheels receiving power, and with the decrease in unit ground pressure attained through the use of an increased number of wheels, dual-tired wheels, and larger pneumatic tires. The application of special traction devices, similar to a half track, to the four dual-tired rear wheels of the six-wheeled vehicle, increases its flotation and improves its tactical mobility to a considerable degree.

The following classes of military vehicles are required for use in combat, or use closely associated with combat, the types of automotive equipment employed or available being indicated in each case:

Class	Type
Tank Combat Car	Special, full track-laying or convertible.
Armored Car *	Special, wheeled, multiwheel drive.
Scout Car	Special, wheeled, 2-wheel or multiwheel drive.
Motor Gun Carriage	Special, full track-laying.
Personnel Carrier	Special, full track-laying or half track.
Artillery Prime Mover	Tractor, half track truck, 2-wheel or multiwheel drive truck.
Cargo Carrier	Half track truck, 2-wheel or multiwheel drive truck.

The first five listed are fighting vehicles. The tank and combat car constitute the basic units of mechanization. They combine to the highest attainable degree the elements of fire power, mobility, and protection. The two classes differ somewhat in design details to meet the

* The armored car is not a required type of vehicle in the United States Army at the present time. Its place is taken by the scout car for reconnaissance and contact missions, and by the combat car for combat missions. It will be included in the discussion of armored combat vehicles in this book, however, not only because it illustrates an interesting phase of development, but also because of the use by other countries of vehicles of this type.

specific requirements of the units to which they pertain, the tank being an infantry weapon and the combat car being the basic weapon of mechanized cavalry. In each case, maximum cross-country ability is essential, and the vehicle must be of the full track type or be capable, selectively, of full track operation.

The armored car is designed primarily as a high-speed road vehicle, with large radius of action, for the performance of reconnaissance and security missions. Its armament may equal that of the combat car, but less protection is afforded by the armor provided. Being a wheeled vehicle, off-road use is limited to favorable terrain.

The scout car may be regarded as a light armored car for use in non-mechanized military units. It compares favorably with the armored car in road speed, radius of action, and armament; less armor protection is afforded. It has restricted mobility on poor roads and across country.

Self-propelled mounts, or motor gun carriages, in which the weapon is permanently mounted on the motor vehicle as a superimposed load for transportation, and for firing, have been tested extensively. At present there is no tactical requirement established for matériel of this class; in lieu of its use, artillery is equipped for high-speed towing by suitable prime movers.

Personnel carriers are designed to transport machine guns or other weapons, with operating crews and essential auxiliary cargo, to and on the battlefield as required for tactical operations. They may be partially armored. They must be capable of cross-country operation.

Artillery prime movers are used to tow artillery. They may be light, medium, or heavy types, according to the loads to be towed, and either of standard commercial design, modified commercial, or of special military design. Standard road performance is essential; the vehicle must have cross-country ability consistent with its tactical use.

Special cargo carriers may be required for use by mechanized forces, capable of cross-country operation and of accompanying the fighting vehicles. Such carriers may be of special design, utilizing the same chassis as other vehicles of the force.

450. World War Tanks.—The special conditions existing on the Western Front after 1914 which made maneuver practically impossible and attack costly and difficult, led to a demand for armored fighting machines capable of cross-country operation, and to the development of the tank by the British in 1916. Wheeled armored cars had been used previously, but their restricted mobility away from improved roads, and the impracticability of installing the heavy armor required for adequate protection, made them of very little value under the conditions existing. The adaptation of the traction principle of the track-

laying or crawler type of tractor, invented and developed by the American Holt, made the tank possible.

Many types of light, medium, and heavy tanks were constructed and used in battle during the last two years of the war. They met, in varying degrees, the basic requirements for mobility on the battlefield, protection of crews by use of armor, and fire power and shock action. The standard types built in quantity in the United States included the 6-ton M1917 Tank, powered with a 40 H.P. engine and equipped either with a 37-mm. gun or a caliber .30 machine gun, and the 35-ton Mark VIII Tank, powered with the 300 H.P. Liberty engine and armed with two 6-pounder guns and a number of machine guns.

All the tanks of this period were characterized by their very low maximum speeds of from 4 to 6 m. p. h., general mechanical unreliability, short operating life, noisy operation, and poor riding qualities. Although attaining some success as mechanical aids to infantry advance, consideration of the mechanical limitations of the vehicle, and of the increased effectiveness of antitank defense measures developed by the end of the war, indicated clearly that marked improvement in performance characteristics was essential if the tank was to develop into an important military weapon.

451. Post-war Development.—To satisfy the requirement for maximum cross-country mobility, it is axiomatic that the tank or similar combat vehicle must be a full track-laying machine. Development efforts were centered on the production of a satisfactory track-laying chassis which would meet the requirements for high speed, mechanical reliability, and durability. Other basic requirements to be met in the design included provision of ample crew space, armor protection of crew and vital mechanical parts, adequate armament and means for its effective use, observation facilities, and communications equipment. The gross weight had to be reduced to the minimum and kept within the maximum weight limitations imposed.

The military characteristics specified vary with the tactical or fighting mission of the machine. However, since the evolution of tank employment tactics is largely dependent upon and follows provision for service use of the latest designs of machines available, and in the absence of adequate opportunity to test tactics and equipment in actual combat, there are many divergent ideas to be reconciled. Certain of the characteristics specified may be conflicting in their effect, or impossible of fulfillment in view of other requirements. For example, in the absence of startling improvement in the quality of armor plate which may not be expected reasonably, full armor protection can only be attained through use of thicker plate, which may not be possible

within the gross weight or other limitations imposed. The demand for larger operating crews and larger crew space results in increase in bulk of the vehicle, area of protective armor, and gross weight. The requirement for high operating speeds affects reliability, durability, and mileage life, and influences weight limitations. Increase in cruising radius cannot be attained without provision of increased fuel capacity. Increase in armament requires increase in space for installation, crew, and ammunition. Accordingly, many compromises must be made, which requires mutual understanding and close cooperation between the designer and the prospective user throughout the development period.

The improvements in the mechanical features of tanks have been accompanied by equally significant advances in the effectiveness and power of tank armament, and in the quality and structural assembly of the armor plate. These subjects are covered in other sections of this book.

In the modern tank or combat vehicle of this type, the conventional assembly of chassis and body employed generally in motor vehicles is replaced by a hull, constructed of armor plate of varying thickness depending upon location, joined together by structural steel angles and rivets. The superstructure may contain one or more turrets of armor plate, which revolve on antifriction bearings. The hull must be kept as small as possible to reduce weight and size of target presented; yet it must house the engine, power train, and other operating equipment, and provide space for the crew, for installation and operation of armament and other equipment, and for ammunition and other supplies. Many factors are affected by the interior arrangements and distribution of space, equipment, and weight, including riding qualities, stability of firing platform, vision of operators, fire hazards, protection of vital parts, etc. The hull is generally divided into compartments, separated by bulkheads for safety and operating convenience. On the outside of the hull are mounted the fuel tanks, suspension system, and final drive units.

Speed, Power and Mobility.—The requirements for rapid acceleration, high road speeds of 45 m. p. h. or more, and high tactical mobility and cross-country speeds of 20 m. p. h., or more, with a wide range of operating speeds and adequate power under adverse conditions, presented many difficult problems. Solution involved consideration of many other related factors, including reliability, mileage life, combat efficiency, etc. Certain of the mechanical units and design features will be discussed.

(*a*) *Engine.*—The speed demanded and restrictions on size and weight do not permit the utilization of rugged heavy-duty engines.

Light, high-speed commercial engines, modified only as necessary for this special service, are employed so far as possible. The continued commercial development of engines and the availability of improved types of smaller size, reduced weight, and greater power have simplified the problem.

The radial air-cooled engine of high power and low weight per horsepower has proved generally satisfactory for tank use. Its adoption removes certain complications and disability hazards involved in the use of water-cooled types of engines, but introduces new cooling problems and requires provision of cooling fans and special shrouding.

The development of the compression-ignition type of oil engine has been so rapid in recent years as to indicate the possibility of its future availability for use in combat vehicles. The advantages obtained would include:

(1) Use of safer fuels and reduction of fire hazards.
(2) Greater fuel economy, with increase in cruising radius for the same fuel capacity.
(3) More suitable torque characteristics.
(4) Elimination of electric ignition system and necessity for radio shielding.

Disadvantages in types of engines now available include difficulty in starting, excessive smoke, and greater weight and size compared to the gasoline engine of the same power. Continued development may lessen these disadvantages and provide units entirely satisfactory for combat use.

(*b*) *Transmission.*—The variation in gear ratios required to permit the wide range of operating speeds specified, the large torque to be transmitted, and the combined requirements of light weight and great strength require design of special transmissions for use in tanks. The type used in the latest vehicles is a 5-speed unit of the constant mesh helical gear type, with manual shifting.

(*c*) *Steering and Final Drive.*—The power train of the high-speed track-laying combat vehicle is necessarily more complex in design than the power train of other vehicles. In the early stages of development, the tracks were driven by rear sprockets, as is the practice in commercial tractors. Proper weight distribution and balance required locating the engine in front when the transmission was in the rear. The later development of satisfactory drive through front sprockets has permitted the shifting of the engine compartment to the rear of the vehicle and the transmission to the front. This permits location of the crew compartment farther forward, simplifying operating controls,

and improving the close-in ground visibility of the operator. The front drive also results in better track ground contact, with greater flotation and improved traction.

In track-laying vehicles designed during the World War and the subsequent early development period, steering was accomplished by use of individual steering clutches and brakes for each track. (Fig. 369.) With both clutches engaged, power is transmitted through the master clutch, transmission gears, and bevel gear to the steering clutch shaft, and thence equally to both drive sprockets. By declutching one side,

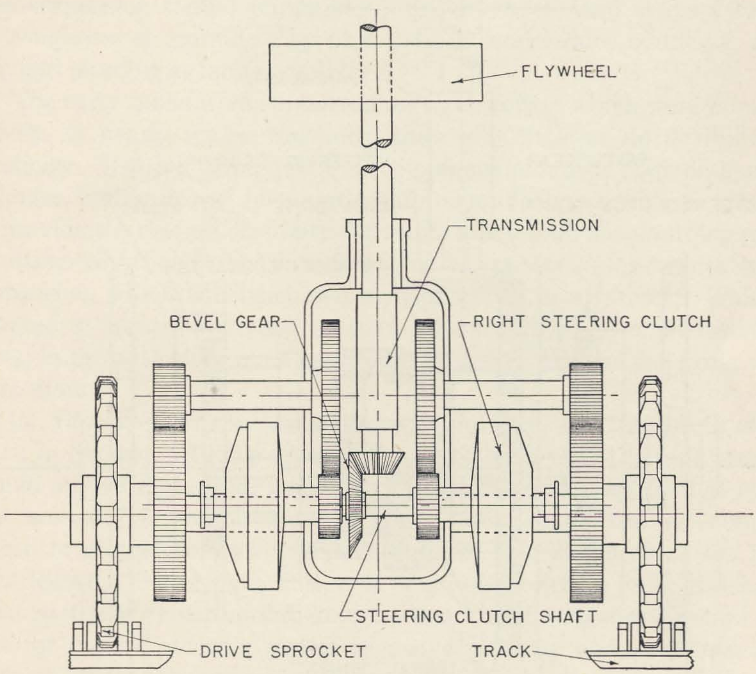


FIG. 369.—Steering by Clutches.

power is transmitted to the opposite track only and the vehicle turns toward the dead track. For sharp pivotal turns the dead track is braked. Although satisfactory for slow-speed vehicles, and having the advantage of permitting a short turning radius, this method of steering is not satisfactory for high-speed machines.

In the controlled-differential type of steering mechanism, the application of a steering brake on one side results in the two tracks being driven at different speeds. Although it does not permit such sharp turns as the conventional clutch type, it is better adapted for high-speed

use, resulting in safer and better controlled driving, less vehicular deceleration in turning, and reduced wear and tear in the power train and tracks.

The construction is illustrated in Fig. 370. When the vehicle is moving straight ahead, not braked on either side, the whole differential assembly rotates as a unit, driven by the bevel gear; the differential and external pinions do not rotate on their bearings, and power is transmitted

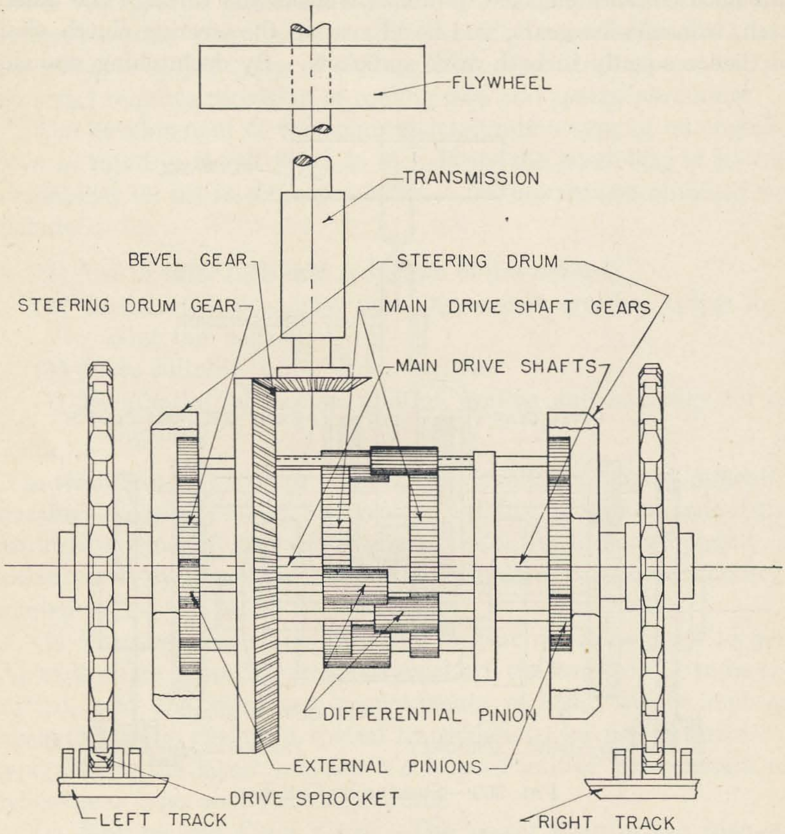


FIG. 370.—Controlled-differential Steering.

equally through the two main drive shaft gears to the driving sprockets. However, if the brake is applied to the right-hand steering drum, for example, it can no longer turn with the differential. The external pinions on that side, being carried around by the rotating differential assembly, must rotate around the stationary steering drum gear; the right differential pinions are rotated in the same direction, driving the left-hand pinions in the opposite direction. The result is that the right-

hand main drive shaft gear is caused to turn more slowly, decreasing the speed of the right track, whereas the rotation of the left main drive shaft gear is speeded up an equal amount. Thus, while power is delivered to both tracks at all times, their relative speeds are changed, resulting in the turning of the vehicle.

(*d*) *Suspension.*—The suspension system of a vehicle consists of the mechanism or means employed to support the body on its road wheels or tracks. In a combat vehicle, which must travel at high speed over varied terrain, an efficient suspension system is essential to vehicular durability, long mileage life, accuracy of fire, and comfort of the crew. The suspension should minimize vibration, shock, and stresses caused by roughness of ground or by obstructions, and reduce bouncing, rocking, and pitching as far as possible.

The early tanks were supported on track rollers which were mounted rigidly, or nearly so, on the hull; there was little or no flexibility or elasticity. During subsequent development, many types of springs, linkages, hydraulic and pneumatic buffers, and other devices were tested to provide the desired elasticity for rough going, and the damping of the resulting vibration. The latest models of tanks employ volute spring suspension, which will be shown in subsequent illustrations. This has resulted in greatly increased mechanical durability, lower maintenance costs, improved riding qualities, and a steadier platform for firing while in motion.

(*e*) *Tracks.*—For maximum tactical mobility, the total area of the track in contact with the ground should be such that the unit pressure should approximate 5 lb. per sq. in., which is equivalent to that of the foot soldier. A combination of wide track shoes and considerable length of ground contact would accomplish this and provide the traction desired. The length and area of ground contact must not be so great as to make steering difficult; on the other hand, short ground contact for ease of steering causes excessive pitching and results in poor bridging or trench-spanning ability. The track must be durable, but as light as possible to minimize power demands and strain on the power drive. The shoes should be of such shape and material as will facilitate traction. The requirements of high road speeds and long track life complicate the problem.

The track was a major source of trouble and cause of mechanical unreliability in the early tanks. It consisted of a heavy continuous articulated band of steel shoes connected by steel pins. Operation even at slow speeds was noisy and required excessive power expenditure; the pins and shoes wore out rapidly and failures due to shock and vibration were frequent. By bushing the pins, providing lubrication, enclosing

pins and bushings for partial protection, and using the best steels available, the steel track gradually was developed to the point where it was reliable for several thousand miles of satisfactory operation at slow speeds. Such tracks were inadequate for high-speed combat vehicles however, having a high rolling resistance and being noisy, injurious to highways, subject to rapid wear, and unduly heavy.

The development of satisfactory rubber tracks has made high-speed road operation of track-laying vehicles possible. A block of rubber is vulcanized about a steel frame or link to form the track shoe, and in a cross tube at each end there is inserted under pressure a steel link pin with a rubber bushing vulcanized to it. End connections are attached to the link pins of adjoining shoes. There is no metal-to-metal contact between shoes and pins. The track pull is transmitted through the rubber bushings and, in the event of constrained angular movement between adjoining shoes, torsion in the rubber bushings causes the joint to resume its normal, unflexed state.

The track is propelled by the engagement of the steel teeth of the driving sprocket with the leading side of the end connections. The bogie wheels, the track-supporting rollers, and the idler wheel at the rear are all rubber-tired.

The advantages of the use of rubber in the tracks and associated units include quieter operation, no injury to highways, reduction of shock and vibration, reduced rolling resistance, safer operation at high speeds, longer mileage life, and practicability of sustained movement on roads at high speed.

452. Modern Track-laying Combat Vehicles.—*The Light Tank.*—The machine illustrated in Fig. 371 is a representative modern tank. The hull is of armor plate, of varying thickness up to $\frac{5}{8}$ in.; it is divided into an engine compartment in the rear, a fighting compartment in the center, and compartments for the driver and front gunner in the bow. Single or double turrets may be used, rotated in azimuth on antifriction bearings by a traversing mechanism, which may be disengaged for free rotation. The armament consists of one caliber .50 and two caliber .30 machine guns. The crew consists of a driver and three gunners. The equipment includes a radio sending and receiving set for both code and voice transmission.

Power from the radial, air-cooled engine in the rear is delivered to the driving sprockets at the front through the clutch, propeller shaft, transmission (5 speeds forward and 1 reverse), controlled differential mounted on a cross shaft, and final drive units mounted at each end of the controlled-differential case. The entire transmission assembly, controlled differential, and final drive units are located in the bow.

The hull is supported by front and rear axles, at the ends of which are mounted 2-wheeled bogies. The construction of the bogie and the

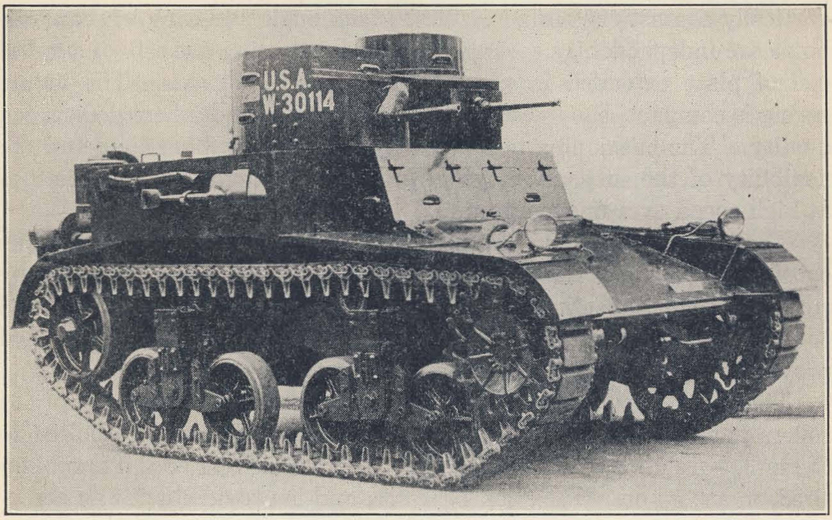


Fig. 371.—Light Tank, M2A2.

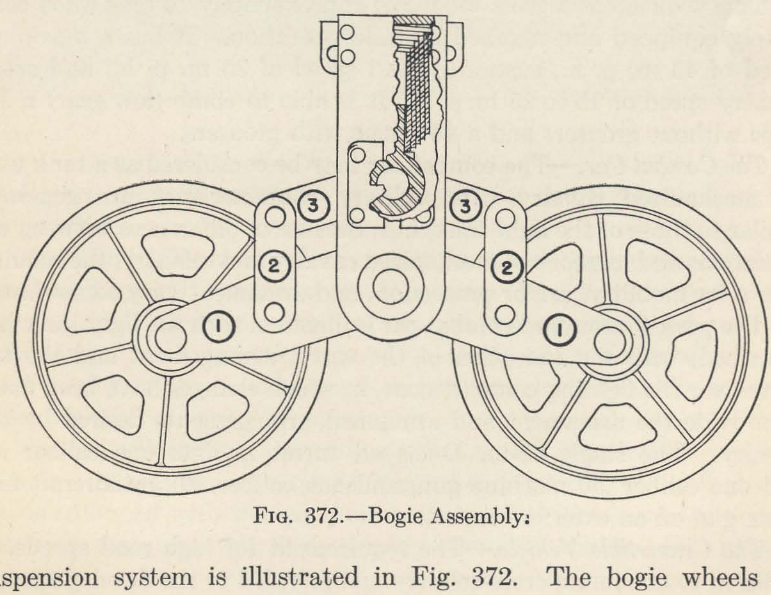


Fig. 372.—Bogie Assembly.

suspension system is illustrated in Fig. 372. The bogie wheels are mounted on arms (1) which pivot around the axle. The independent vertical movement of each wheel, as the track beneath it moves up

owing to ground inequalities, is transmitted through the link (2) to the rocker arm (3). The rocker arm is pivoted on a pin which mounts two plugs forming seats for the two sets of volute springs, and can move vertically against the springs. Thus, each bogie and each wheel of the bogie are independently sprung. The volute spring consists of a spiral coil of plate extended in the direction of the coil axis. The volute spring is compact, has satisfactory elastic action, and inherent damping quality. The cushioning permitted by the use of rubber tires and the flexibility of the suspension sytem provide satisfactory riding qualities at high speed over uneven ground.

The track is composed of a belt of rubber block units, each of which consists of a steel frame covered with rubber, joined together by rubber-bushed link pins and end connections of alloy steel. The end connections also keep the track in line on the supporting rollers, and provide lugs which engage the teeth of the driving sprocket.

The track is supported vertically on rubber-tired track supporting rollers mounted on antifriction bearings on spindle brackets bolted to the hull. An idler wheel supports the track at the rear end; it is rubber-tired, mounted on antifriction bearings, and is provided with an eccentric adjustment by means of which the tension of the track may be varied.

This vehicle has a gross weight of approximately 10 tons when completely equipped and manned for field operation. It has a maximum speed of 45 m. p. h., sustained road speed of 35 m. p. h., and cross-country speed of 15 to 25 m. p. h. It is able to climb (low gear) a 20° slope without grousers and a 45° slope with grousers.

The Combat Car.—The combat car may be considered as a tank used by mechanized cavalry. Its military characteristics are generally similar to those of the light tank, but, because of differences between the operations and missions of mechanized cavalry and infantry, the requirements for mobility, armor protection, and armament vary somewhat.

The present standard combat car is identical with the light tank just described, with the exception of the turret arrangement and the top plate over the fighting compartment, in which changes have been made to provide the armament and armament arrangements desired by the cavalry. The single 48-in. D-shaped turret mounts one caliber .30 and one caliber .50 machine gun, and one caliber .30 antiaircraft machine gun on an exterior bracket.

The Convertible Vehicle.—The requirement for high road speeds, in addition to maximum cross-country mobility, led to the development of the convertible type of vehicle. (Fig. 373.) For operation off roads, the track is driven by a driving sprocket at the rear. The hull is sup-

ported on each side by four large rubber-tired wheels, individually spring-suspended on cantilever arms attached to the hull. For road operation as a wheeled vehicle, the track is broken at one or more joints, removed, and placed on the shelf provided above. Driving chains are installed between the driving sprockets and rear road wheels and the two intermediate wheels on each side are lifted by screws, thus converting the vehicle to a 4-wheel, 2-wheel drive machine. Steering is accomplished through use of the controlled differential when operating on

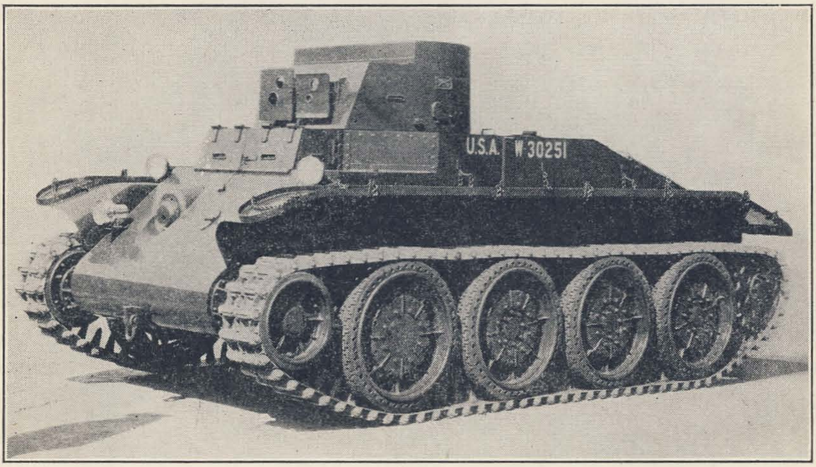


FIG. 373.—Convertible Tank.

tracks, but conventional front-wheel steering is employed when operating on wheels.

The convertible vehicle has certain apparent advantages for high-speed road use and continued developmental effort is warranted if road speeds beyond those permitted by straight track-laying types are to be demanded. In its present state of development, the convertible machine is unduly heavy and complicated, which defects may be inherent in such a multiple-purpose machine.

The tank illustrated is a medium type, with a gross weight of about 13 tons. It uses the same type of engine as the light tank and combat car, is equipped with the same armament and thickness of armor, and has approximately the same speed, climbing ability, and fighting capacity.

453. Half Track Vehicles.—Figure 374 illustrates the conversion of standard commercial wheeled vehicles by substitution of short track-laying units for the rear wheels. The increase in traction and mobility

for off-road use make these machines, when of suitable type and power, well adapted for military use as prime movers, personnel carriers, and for general transport purposes where battlefield mobility is required.

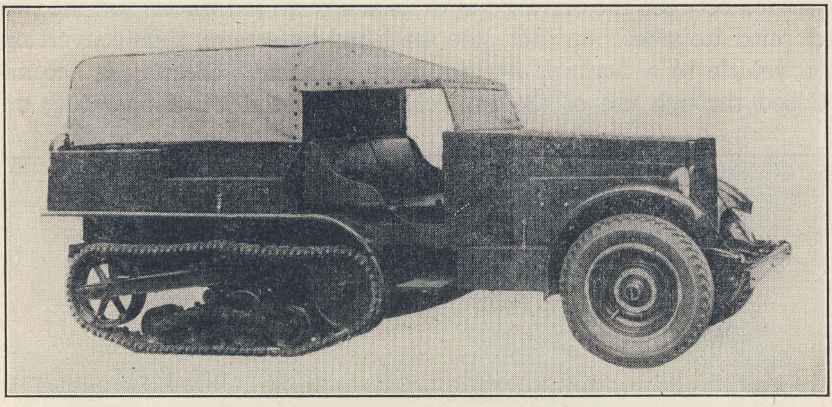


FIG. 374.—Half Track Truck.

Other advantages include low cost as compared with vehicles of special military design, availability in quantity except for the relatively simple suspension and tracks, and continuous commercial development.

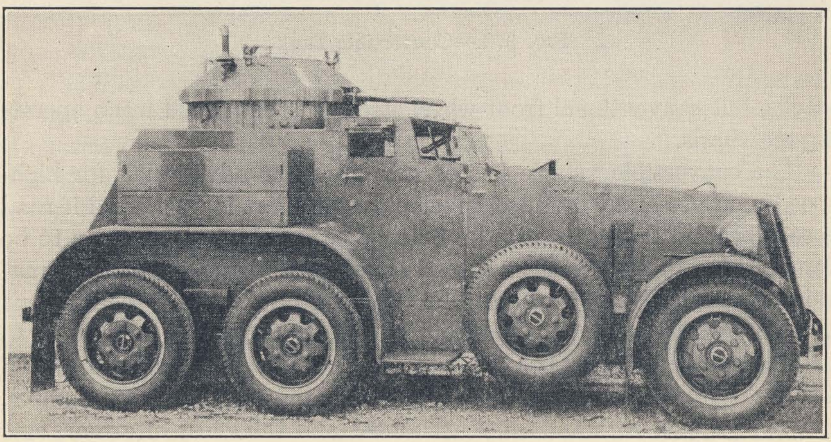


FIG. 375.—Armored Car, M1.

454. Wheeled Combat Vehicles.—*Armored Cars.*—The armored cars built in the decade following the World War were constructed on standard commercial 4-wheel, 2-wheel drive passenger car chassis.

These lacked durability for the severe service required of them, and were deficient in other respects.

To meet specified military requirements, the Armored Car, M1, illustrated in Fig. 375, was developed and standardized. It was of special design throughout, of 6-wheel, 4-wheel drive type. The armament included one caliber .50 and two caliber .30 machine guns, and it was armored with plate varying from $\frac{3}{16}$ in. to $\frac{1}{2}$ in., according to location. The gross weight was slightly under 5 tons. It had high road speed and was capable of distant action, but had restricted mobility on bad roads and across country and limited close-in ground observation.

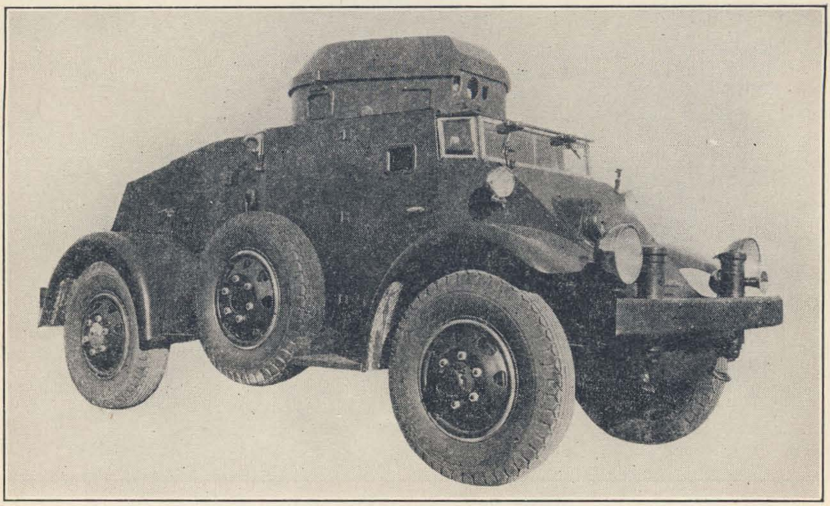


FIG. 376.

A later armored car, of the 4-wheel, 4-wheel drive type, is illustrated in Fig. 376. It has better off-road mobility characteristics than the M1 six-wheeler type, and locating the engine in the rear gave better balance and close-in visibility. The two vehicles require the same crew (4 men), and have the same armament, degree of armor protection, and fighting capacity. They are unduly heavy, and being of special design throughout, are costly. Quantity procurement would be difficult.

As previously stated, the armored car is no longer a required type of vehicle in the United States Army and further development is not contemplated.

The Scout Car.—The scout car illustrated in Fig. 377 is a light armored car used in reconnaissance and in special situations for harassing

and delaying missions. The armored body is constructed on a light commercial 4-wheel, 4-wheel drive truck chassis. It has a high road speed but restricted mobility on poor roads and across country. It has the advantages of low cost, quantity availability of chassis, and continuous commercial development. The armament consists of one caliber .50 and two caliber .30 machine guns mounted on the outside of the car body. The latest models of scout cars are equipped with a continuous track near the top edge of the armor plate on which may be installed several aircraft machine gun mounts. Each mount may be readily rolled around the track to the position desired.

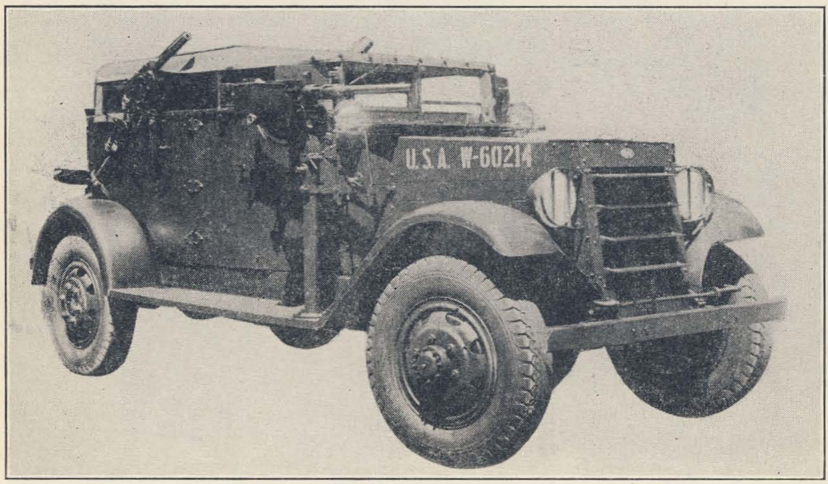


FIG. 377.—Scout Car, M1.

The use of multiwheel drives, low-pressure pneumatic tires, dual-tired wheels, and various traction devices which can be applied over the tires has greatly increased the cross-country ability of all wheeled vehicles. Tire vulnerability has been reduced by use of puncture-sealing inner tubes.

PROVING-GROUND TESTS

The Proving Ground provides facilities for testing all types of military vehicles and accessory units. Engineering data are obtained concerning the performance of various vehicular components, and the complete vehicles are subjected to field tests to determine their capabilities under severe operating conditions, to detect defects, and to determine their suitability for the performance of their particular missions.

455. Laboratory Tests.—The electric dynamometer is used to measure engine horsepower and torque. The complete set of engine test curves includes the following, which are plotted against engine revolutions per minute:

Torque	Fuel consumption
Indicated horsepower	Mechanical efficiency
Brake horsepower	Friction horsepower

The equipment enables the determination of losses and efficiencies in all parts of the system, from the engine and its accessories through the clutch, transmission, differential, and final drive to the driving sprockets or rear axle.

Electric dynamometers are employed in the track testing machine to determine the power losses in the operation of various types of tracks, independently of the vehicles on which they are to be mounted and of all other factors. This permits efficiency comparisons.

456. Field Tests.—Tests to determine power, strength, mechanical reliability, and performance capabilities of complete vehicles include the following features and equipment:

Field Dynamometer.—The field or traction dynamometer, M3, is a 6-wheel, 4-wheel drive truck, on which is installed a power-absorbing mechanism, a recording device, and sensitive fore and aft drawbars. The dynamometer is towed by the vehicle undergoing test, to determine its drawbar pull or useful horsepower delivered at the drawbar, over varied courses including concrete, gravel, sand, mud, etc. The dynamometer is also used as a towing vehicle to determine the resistance of any vehicle to traction as a function of speed. Fuel-consumption tests are made in conjunction with the dynamometer to determine accurately the fuel used at various drawbar horsepower loads.

Accelerometer.—This device records accurately the time-distance relation of the moving vehicle. The data obtained are used in the determination of such factors as vehicular acceleration under various conditions, deceleration due to braking, climbing, or traction resistance, etc.

Sand Course.—This consists of a concrete box 500 ft. long, 20 ft. wide, and 18 in. deep, filled with dry washed sand through which the vehicle is driven or towed. Although representing an extreme terrain condition, the relative performances of various vehicles through this course, and their drawbar pulls as measured by the dynamometer, are indicative of their comparative cross-country ability.

Mud Course.—This consists of a similar open concrete box 300 ft. long, containing two 12-ft. roads, 2 and 3 ft. deep, filled with a mixture

of loam and clay which is sprinkled until the desired degree of muddiness is obtained. By standardizing conditions, the relative mud performance of various vehicles may be determined. As in sand, mobility through the mud course depends upon the flotation area of tires or tracks. Ground clearance of the vehicle is an important feature since, if penetration is sufficient to bring the body or parts in contact with the mud, the resistance and power requirements will be greatly increased.

In both sand and mud, the full track-laying vehicle demonstrates superior performance. Traction devices added to wheeled vehicles improve their performance.

Water Course.—This consists of an open concrete tank 250 ft. long by 4 ft. deep at the center, the depth decreasing towards both ends. It is used for two types of tests. Maximum fording ability is determined by gradually increasing the depth of the water. The effect of high-speed operation is determined at speeds of about 30 m. p. h., through water about 1 ft. deep, and vehicular deficiencies in this respect noted.

Washboard Course.—This consists of a series of concrete blocks or humps on each side of the course, of varying heights and set at varying intervals. It is used to measure the flexibility of suspension systems under extreme conditions, and the strength and resistance to distortion of bodies and frames.

Slope Course.—This consists of a series of straight roads of different slopes. The roads with 5, 10, 15, and 20 per cent grades have smooth gravel surfaces, whereas the 30, 40, 50, and 60 per cent slopes are timber-revetted to prevent washing. This course is used to measure the slope performance of the vehicle, including maximum speed on the various grades, most suitable gear for best performance, traction, and holding ability of brakes. Side slope courses are used to test the ability of vehicles to operate on side slopes without overturning.

The size and power of the engine are fixed by the vehicular speed performance required on slopes, the acceleration characteristics on level ground, and requirement of reasonable speed and mobility over varied terrain, which may be sandy, muddy, and with steep grades.

Other Tests.—The bridging device determines the bridging capacity, or the width of trench or gap the track-laying vehicle can cross by spanning. This consists of a concrete box with a movable top which can be adjusted to provide gaps up to $11\frac{1}{2}$ ft. Standard trenches are also employed.

Vertical walls with height of 1, 2, and 3 ft. are used to determine the ability of vehicles to climb over obstructions, interference of parts in climbing, and tendency to tip backwards. The height which can be surmounted by the track-laying vehicle depends upon its length. The

wheeled vehicle powered only in rear has very little climbing ability; with the 100 per cent drive feature, wheeled vehicles are able to climb walls of a height approximately equal to the front wheel radius.

A circular cobblestone bowl, at the center of which is a motor-driven turn-table to which the vehicle may be attached and towed by means of a long arm, is used to facilitate determination of vehicular strength and resistance to the severe shocks and strains incident to cross-country travel. Speeds up to 18 m. p. h. may be attained and maintained throughout as long a test period as desired.

A pitch, roll, and vertical acceleration recorder is used to determine accurately the riding characteristics of vehicles and relative body stability on standard-obstacled roads at various speeds. The instrument measures and records the movements of the longitudinal and transverse body axes with reference to the ground, and the vertical movements of the body, and is equipped with a time-distance recorder.

Other instruments, such as ride meters, sound meters, machine gun cameras, etc., are used to obtain and record data bearing on vehicular performance or qualities.

Cross-country Course.—Cross-country endurance runs of long duration, over all kinds of terrain and in all kinds of weather, may be used to test mechanical reliability and to determine design or material weaknesses under long-continued use.

Track-testing Machine.—This installation provides for laboratory endurance testing of the tracks and suspension systems of combat vehicles without the expense incident to the use of the vehicles themselves. The tracks and suspension parts to be tested are mounted on a frame representing one side of the track-laying vehicle and attached to a 4-wheel carriage running on a circular rail guideway approximately one-fifth of a mile in length. The position of the frame on the carriage may be adjusted laterally so that the track undergoing test will run on gravel, undulating concrete, or smooth concrete roadways provided between the rails. The machine is propelled around the course by the track, power to the driving sprocket being provided by an electric motor which receives energy from a third-rail system.

APPENDIX

GREEK ALPHABET

A	α	Alpha.	N	ν	Nu.
B	β	Beta.	Ξ	ξ	Xi.
Γ	γ	Gamma.	O	o	Omicron.
Δ	δ	Delta.	Π	π	Pi.
E	ϵ	Epsilon.	P	ρ	Rho.
Z	ζ	Zeta.	Σ	σ or s	Sigma.
H	η	Eta.	T	τ	Tau.
Θ	θ	Theta.	Υ	υ	Upsilon.
I	ι	Iota.	Φ	ϕ	Phi.
K	κ	Kappa.	X	χ	Chi.
Λ	λ	Lambda.	Ψ	ψ	Psi.
M	μ	Mu.	Ω	ω	Omega.

TABLE I

INTERNATIONAL ATOMIC WEIGHTS, 1937

	Symbol	Atomic Number	Atomic Weight		Symbol	Atomic Number	Atomic Weight
Aluminum	Al	13	26.97	Mercury	Hg	80	200.61
Antimony	Sb	51	121.76	Molybdenum	Mo	42	96.0
Argon	A	18	39.944	Neodymium	Nd	60	144.27
Arsenic	As	33	74.91	Neon	Ne	10	20.183
Barium	Ba	56	137.36	Nickel	Ni	28	58.69
Beryllium	Be	4	9.02	Nitrogen	N	7	14.008
Bismuth	Bi	83	209.00	Osmium	Os	76	191.5
Boron	B	5	10.82	Oxygen	O	8	16.0000
Bromine	Br	35	79.916	Palladium	Pd	46	106.7
Cadmium	Cd	48	112.41	Phosphorus	P	15	31.02
Calcium	Ca	20	40.08	Platinum	Pt	78	195.23
Carbon	C	6	12.01	Potassium	K	19	39.096
Cerium	Ce	58	140.13	Praseodymium	Pr	59	140.92
Cesium	Cs	55	132.81	Radium	Ra	88	226.05
Chlorine	Cl	17	35.457	Radon	Rn	86	222.
Chromium	Cr	24	52.01	Rhodium	Rh	45	102.91
Cobalt	Co	27	58.94	Rubidium	Rb	37	85.48
Columbium	Cb	41	92.91	Ruthenium	Ru	44	101.7
Copper	Cu	29	63.57	Samarium	Sm	62	150.43
Dysprosium	Dy	66	162.46	Scandium	Sc	21	45.10
Erbium	Er	68	167.64	Selenium	Se	34	78.96
Europium	Eu	63	152.0	Silicon	Si	14	28.06
Fluorine	F	9	19.00	Silver	Ag	47	107.880
Gadolinium	Gd	64	156.9	Sodium	Na	11	22.997
Gallium	Ga	31	69.72	Strontium	Sr	38	87.63
Germanium	Ge	32	72.60	Sulphur	S	16	32.06
Gold	Au	79	197.2	Tantalum	Ta	73	180.88
Hafnium	Hf	72	178.6	Tellurium	Te	52	127.61
Helium	He	2	4.002	Terbium	Tb	65	159.2
Holmium	Ho	67	163.5	Thallium	Tl	81	204.39
Hydrogen	H	1	1.0078	Thorium	Th	90	232.12
Indium	In	49	114.76	Thulium	Tm	69	169.4
Iodine	I	53	126.92	Tin	Sn	50	118.70
Iridium	Ir	77	193.1	Titanium	Ti	22	47.90
Iron	Fe	26	55.84	Tungsten	W	74	184.0
Krypton	Kr	36	83.7	Uranium	U	92	238.07
Lanthanum	La	57	138.92	Vanadium	V	23	50.95
Lead	Pb	82	207.21	Xenon	Xe	54	131.3
Lithium	Li	3	6.940	Ytterbium	Yb	70	173.04
Lutecium	Lu	71	175.0	Yttrium	Y	39	88.92
Magnesium	Mg	12	24.32	Zinc	Zn	30	65.38
Manganese	Mn	25	54.93	Zirconium	Zr	40	91.22

Data for this Table furnished by Picatinny Arsenal.

TABLE II

DENSITIES OF CERTAIN GASES AT 0° C. AND 760-MM. PRESSURE

Gas	Formula	Density Air = 1	Lb. per Cu. Ft.	Cu. Ft. per Lb.
Acetylene	C_2H_2	0.9073	.07324	13.654
Air[1]	......	1.0000	.08072	12.390
Ammonia	NH_3	0.5963	.04813	20.777
Bromine[2]	Br_2	5.516	.44525	2.246
Carbon dioxide	CO_2	1.5290	.12342	8.102
Carbon monoxide	CO	0.9671	.07806	12.810
Chlorine	Cl_2	2.49	.20099	4.975
Coal gas	......	0.504	.04068	24.58
Cyanogen	C_2N_2	1.804	.14562	6.867
Ethane	C_2H_6	1.0493	.08470	11.806
Ethylene	C_2H_4	0.9710	.07838	12.758
Fluorine	F_2	1.312	.1059	9.443
Helium	He	0.1381	.01115	89.69
Hydrogen	H_2	0.06952	.005612	178.19
Hydrogen bromide	HBr	2.8189	.22754	4.395
Hydrogen chloride	HCl	1.2678	.10234	9.771
Hydrogen fluoride	HF	0.713	.0576	17.361
Hydrogen iodide	HI	4.4776	.3614	2.767
Hydrogen sulphide	H_2S	1.190	.09606	10.411
Methane	CH_4	0.5544	.0448	22.32
Nitric oxide	NO	1.0366	.08367	11.953
Nitrogen	N_2	0.9673	.07808	12.807
Nitrogen dioxide[2]	NO_2	1.588	.1282	7.800
Nitrogen tetroxide[2]	N_2O_4	3.176	.2564	3.900
Nitrous oxide	N_2O	1.530	.12350	8.097
Oxygen	O_2	1.1053	.08922	11.208
Steam (at 100° C.)	H_2O	0.4618[3]	.03728	26.824
Sulphur dioxide	SO_2	2.2638	.18273	5.473
Water gas	......	0.684	.05521	18.11

[1] Dry atmospheric air at sea level has approximately the following composition by volume:

	Per Cent		Per Cent
N_2	78.03	CO_2	0.03
O_2	20.99	H_2	0.01
A	0.94	Rare gases	0.002

[2] Not gaseous under standard conditions. Density is calculated assuming molecular volume equal to 22.411 liters.

[3] Compared to air at 0° C.

Data for this Table furnished by Picatinny Arsenal.

TABLE III

Specific Heats at Room Temperatures, Solids and Liquids

Name	Formula	Molecular Weight	Specific Heats	
			Calories per Gram	Calories per Gram Molecule or Gram Atom
Alcohol (liquid)	C_2H_5OH	46.1	0.581	26.8
Aluminum oxide	Al_2O_3	101.9	0.188	19.2
Ammonium chloride	NH_4CL	53.5	0.376	20.1
Ammonium nitrate	NH_4NO_3	80.0	0.407	32.6
Antimony	Sb	121.76	0.0503	6.12
Antimonous oxide	Sb_2O_3	291.5	0.0829	24.2
Arsenic (metallic)	As	74.91	0.0822	6.16
Barium carbonate	$BaCO_3$	197.4	0.1030	20.3
Barium chloride	$BaCL_2$	208.3	0.0875	18.2
Barium nitrate	$Ba(NO_3)_2$	261.4	0.1523	39.8
Benzene (liquid)	C_6H_6	78.1	0.406	31.7
Calcium carbonate	$CaCO_3$	100.1	0.206	20.6
Calcium chloride	$CaCl_2$	111.0	0.1642	18.2
Calcium sulphate (cryst. anhyd.)	$CaSO_4$	136.1	0.169	23.0
Carbon (graphite)	C	12.01	0.165	1.98
Chromium trioxide	Cr_2O_3	152.0	0.178	27.1
Copper sulphate (anhydrous)	$CuSO_4$	159.6	0.157	25.1
Glycerin (liquid)	$C_3H_5(OH)_3$	92.1	0.580	53.4
Iron sulphide	FeS	87.9	0.139	12.2
Lead	Pb	207.21	0.0305	6.32
Lead carbonate	$PbCO_3$	267.2	0.0971	26.0
Lead nitrate	$Pb(NO_3)_2$	331.2	0.1173	38.8
Magnesia	MgO	40.3	0.235	9.46
Mercury (liquid)	Hg	200.61	0.03325	6.67
Nitric acid (liquid)	HNO_3	63.02	0.476	30.00
Phosphorus (Red)	P_4	124.08	0.1829	22.7
Potassium dichromate	$K_2Cr_2O_7$	294.2	0.182	53.5
Potassium carbonate	K_2CO_3	138.2	0.2162	29.9
Potassium chlorate	$KClO_3$	122.6	0.196	24.00
Potassium chloride	KCl	74.6	0.164	12.2
Potassium ferrocyanide	$K_4Fe(CN)_6$	368.3	0.218	80.3
Potassium nitrate	KNO_3	101.1	0.220	22.2
Potassium perchlorate	$KClO_4$	138.6	0.191	26.5
Potassium sulphate (cryst.)	K_2SO_4	174.3	0.182	31.7
Potassium sulphide	K_2S	110.3	0.091	10.0
Silica (quartz)	SiO_2	60.1	0.188	11.3
Silver	Ag	107.880	0.05625	6.07
Silver chloride (cryst.)	AgCl	143.3	0.0878	12.6
Silver nitrate (fused)	$AgNO_3$	169.9	0.144	24.5
Sodium carbonate	Na_2CO_3	106.0	0.2728	28.9
Sodium chloride	NaCl	58.5	0.208	12.2
Sodium nitrate	$NaNO_3$	85.0	0.259	22.0
Sodium sulphate	Na_2SO_4	142.1	0.207	29.4
Sodium sulphide	Na_2S	78.1	0.091	7.11
Strontium nitrate	$Sr(NO_3)_2$	211.6	0.182	38.5
Strontium sulphate	$SrSO_4$	183.7	0.1428	26.2
Sulphur (Rhombic)	S_2	64.12	0.1728	11.1
Sulphuric acid (liquid)	H_2SO_4	98.1	0.345	33.8
Water	H_2O	18.0	1.000	18.0

Data for this Table furnished by Picatinny Arsenal.

TABLE IV

Heats of Formation from the Elements at 15° C. and 760-mm. Pressure

Name	Formula	Molecular Weight	Heats of Formation in Large Calories per Gram Molecule			
			Gas	Liquid	Solid	Dissolved
Acetone	CH_3COCH_3	58.1	53.4	61.5	...	64.0
Acetylene	C_2H_2	26.0	−54.86			
Ammonia	NH_3	17.0	10.9	15.8	...	19.1
Ammonium bicarbonate	NH_4HCO_3	79.1	...	...	208.6	
Ammonium chloride	NH_4Cl	53.5	38.9	...	76.8	72.8
Ammonium dichromate	$(NH_4)_2Cr_2O_7$	252.1	...	...	420.1	407.4
Ammonium nitrate	NH_4NO_3	80.0	...	...	88.1	82.8
Ammonium picrate	$C_6H_2(NO_2)_3O \cdot NH_4$	246.1	...	...	78.0	69.3
Aniline	$C_6H_5NH_2$	93.1	...	−6.4	−4.3	−6.6
Antimonic oxide	Sb_2O_5	323.5	...	...	230.9	
Antimonous oxide	Sb_2O_3	291.5	...	...	166.9	
Antimony sulphide	Sb_2S_3	339.7	...	...	34.4	
Barium chlorate	$Ba(ClO_3)_2$	304.3	...	...	171.2	167.2
Barium oxide	BaO	153.4	...	...	133.1	169.1
Barium nitrate	$Ba(NO_3)_2$	261.4	...	...	238.3	180.0
Barium peroxide	BaO_2	169.4	...	...	151.7	
Benzene	C_6H_6	78.1	−16.8	−12.0	−9.7	
Calcium picrate	$[C_6H_2(NO_2)_3O]_2Ca$	496.3	...	...	185.4	187.6
Camphor	$C_{10}H_{16}O$	152.2	...	...	79.8	
Cane sugar	$C_{12}H_{22}O_{11}$	342.3	...	...	535.0	
Carbon dioxide	CO_2	44.0	94.39	...	100.3	99.1
Carbon disulphide	CS_2	76.1	−25.4	−19.0		
Carbon monoxide	CO	28.0	26.43			
Cellulose	$C_{24}H_{40}O_{20}$	648.6	...	...	920.9	
Cellulose acetate (penta)	$C_6H_5(O_2CCH_3)_5$	372.3	...	...	520.0	
Copper picrate	$[C_6H_2(NO_2)_3O]_2Cu$	519.8	...	...	60.4	63.7
Cyanogen	C_2N_2	52.0	−66.7	−65.5	...	−64.0
Dextrine	$C_6H_{10}O_5$	162.1	...	...	242.0	
Dibutylphthalate	$C_6H_4(CO_2C_4H_9)_2$	278.3	...	...	199.8	
Diethylphthalate	$C_6H_4(CO_2C_2H_5)_2$	222.2	...	...	180.3	
Dinitrobenzene (ortho)	$C_6H_4(NO_2)_2$	168.1	...	...	−0.2	
Dinitrobenzene (meta)	$C_6H_4(NO_2)_2$	168.1	...	...	6.0	
Dinitrobenzene (para)	$C_6H_4(NO_2)_2$	168.1	...	...	8.0	
Dinitronaphthalene (1 : 8)	$C_{10}H_6(NO_2)_2$	218.2	...	...	−2.7	
Dinitrophenol (2 : 3)	$C_6H_3OH(NO_2)_2$	184.1	...	...	14.0	
Dinitrophenol (2 : 4)	$C_6H_3OH(NO_2)_2$	184.1	...	...	55.6	
Dinitrophenol (2 : 6)	$C_6H_3OH(NO_2)_2$	184.1	...	...	17.0	
Dinitrotoluol (2 : 4)	$C_6H_3CH_3(NO_2)_2$	182.1	...	...	12.2	
Dinitrotoluol (3 : 4)	$C_6H_3CH_3(NO_2)_2$	182.1	...	...	5.1	
Dinitrotoluol (3 : 5)	$C_6H_3CH_3(NO_2)_2$	182.1	...	...	12.0	
Diphenylamine	$C_6H_5NH \cdot C_6H_5$	169.2	...	−22.2	−27.6	
Ethane	C_2H_6	30.1	25.5			
Ethyl alcohol	C_2H_5OH	46.1	56.0	66.3	...	69.2
Ethyl ether	$(C_2H_5)_2O$	74.1	39.1	46.8		
Ethylene	C_2H_4	28.1	−6.5			
Formaldehyde	CH_2O	30.0	28.8	...	...	40.4
Glucose	$CH_2OH(CHOH)_4CH \cdot O$	180.2	...	...	303.6	276.
Glycerin (glycerol)	$CH_2OH \cdot CHOH \cdot CH_2OH$	92.1	...	159.7	163.6	165.1
Glycol	$(CH_2OH)_2$	62.1	99.9	112.0	...	99.9
Glycol dinitrate	$C_2H_4(NO_3)_2$	152.1	...	58.7		
Guanidine	$C(NH)(NH_2)_2$	59.1	...	...	19.2	28.4
Guanidine nitrate	$CH_5N_3NO_3H$	122.1	...	...	79.3	89.2
Hydrocellulose	$C_{12}H_{22}O_{11}$	342.3	...	...	453.8	
Hydrogen peroxide	H_2O_2	34.0	...	46.84	56.0	45.3
Hydrogen sulphide	H_2S	34.1	5.26	9.26	...	9.32
Lead azide	PbN_6	291.3	...	...	−105.9	
Lead oxide	PbO	223.2	...	...	52.47	
Lead nitrate	$Pb(NO_3)_2$	331.2	...	...	108.3	101.7
Lead picrate	$[C_6H_2(NO_2)_3O]_2Pb$	663.4	...	...	82.2	75.1
Magnesium picrate	$[C_6H_2(NO_2)_3O]_2Mg$	480.5	...	...	172.6	187.3
Mannite	$(CH_2OH)_2(CHOH)_4$	182.2	...	...	317.9	282.4
Mannitol hexanitrate	$C_6H_8(NO_3)_6$	452.2	...	179.1		
Mercuric oxide	HgO	216.6	...	...	21.7	
Mercury fulminate	$Hg(CNO)_2$	284.6	...	...	−64.5	
Mercury picrate	$[C_6H_2(NO_2)_3O]_2Hg$	656.3	...	...	42.8	38.1
Methane	CH_4	16.0	20.3			
Methyl nitrate	$CH_3O \cdot NO_2$	77.0	39.9			
Mononitrobenzene	$C_6H_5NO_2$	123.1	−11.7	−2.0	0.7	

TABLE IV—*Continued*

HEATS OF FORMATION FROM THE ELEMENTS AT 15° C. AND 760-MM. PRESSURE

Name	Formula	Molecular Weight	Heats of Formation in Large Calories per Gram Molecule			
			Gas	Liquid	Solid	Dissolved
Nitric acid	HNO_3	63.0	35.3	42.4	43.0	49.8
Nitric oxide	NO	30.0	−21.6			
Nitroacetanilide (ortho)	$C_8H_8N_2O_3$	180.2	....	....	52.6	
Nitroacetanilide (meta)	$C_8H_8N_2O_3$	180.2	....	....	54.6	
Nitroacetanilide (para)	$C_8H_8N_2O_3$	180.2	....	....	60.6	
Nitrobenzaldehyde (ortho)	$C_6H_4CHONO_2$	151.1	....	19.9		
Nitrobenzaldehyde (meta)	$C_6H_4CHONO_2$	151.1	....	19.9	31.6	
Nitrobenzaldehyde (para)	$C_6H_4CHONO_2$	151.1	....	19.9	44.1	
Nitrocamphor (alpha)	$C_{10}H_{15}(NO_2)O$	197.2	....	....	85.4	
Nitrocamphor (phenol)	$C_{10}H_{15}(NO_2)O$	197.2	....	....	125.2	
Nitrocellulose (12.6%N)	$C_{24}H_{30.19}O_{10.19}(NO_3)_{9.81}$	1090.0	....	....	665.5	
Nitrocellulose (12.75%N)	$C_{24}H_{30}O_{10}(NO_3)_{10}$	1098.6	....	....	659.3	
Nitrocellulose (13.15%N)	$C_{24}H_{29.45}O_{9.45}(NO_3)_{10.55}$	1123.3	....	....	643.1	
Nitrocellulose (13.75%N)	$C_{24}H_{29.32}O_{9.31}(NO_3)_{10.69}$	1129.6	....	....	639.9	
Nitroethane	$C_2H_5NO_2$	75.1	30.6	37.5		
Nitrogen chloride	NCl_3	120.4	....	−38.5	....	−54.8 in CCl_4
Nitrogen pentoxide	N_2O_5	108.0	−1.2	3.6	14.6	28.6
Nitrogen peroxide	NO_2	46.0	−7.4	−12.6	....	25.6
Nitrogen sulphide	N_4S_4	184.3	−19.0	....	−31.9	
Nitrogen trioxide	N_2O_3	76.0	−21.4	....	....	−14.7
Nitroglycerin	$C_3H_5(NO_3)_3$	227.1	....	85.3		
Nitroguanidine	$C\cdot NH\cdot NH_2\cdot NHNO_2$	104.1	....	....	12.6	
Nitromethane	CH_3NO_2	61.0	14.0	27.6		
Nitronaphthalene (alpha)	$C_{10}H_7NO_2$	173.2	....	−2.2	−7.1	
Nitrophenol (ortho)	$C_6H_4NO_2OH$	139.1	....	−56.1	47.2	
Nitrophenol (para)	$C_6H_4NO_2OH$	139.1	....	−57.0	50.1	
Nitrous oxide	N_2O	44.0	−17.0	−18.7	....	−14.4
Ozone	O_3	48.0	−34.4	....	....	−32.5
Picric acid	$C_6H_2(NO_2)_3OH$	229.1	....	....	56.0	
Potassium carbonate	K_2CO_3	138.2	....	....	275.0	281.5
Potassium chlorate	$KClO_3$	122.6	....	....	89.9	79.5
Potassium chloride	KCl	74.6	....	....	104.3	99.9
Potassium dichromate	$K_2Cr_2O_7$	294.2	....	....	481.7	
Potassium nitrate	KNO_3	101.1	....	114.2	119.0	110.14
Potassium perchlorate	$KClO_4$	138.6	....	....	113.5	100.2
Potassium picrate	$C_6H_2(NO_2)_3OK$	267.2	....	....	110.1	100.1
Potassium sulphate	K_2SO_4	174.3	....	....	338.5	
Silver nitrate	$AgNO_3$	169.9	....	16.0	30.11	24.66
Sodium carbonate	Na_2CO_3	106.0	....	....	272.6	276.2
Sodium chlorate	$NaClO_3$	106.5	....	79.6	82.34	77.06
Sodium chloride	$NaCl$	58.5	....	90.7	98.4	97.1
Sodium nitrate	$NaNO_3$	85.0	....	106.0	112.5	107.4
Sodium perchlorate	$NaClO_4$	122.5	....	....	100.3	97.25
Sodium picrate	$C_6H_2(NO_2)_3ONa$	251.1	....	....	103.4	97.0
Sodium sulphide	Na_2S	78.1	....	....	89.7	105.5
Starch	$(C_6H_{10}O_5)_x$	162.1	....	....	230.8	
Strontium nitrate	$Sr(NO_3)_2$	211.6	....	....	234.4	230.6
Strontium oxide	SrO	103.6	....	....	140.7	237.1
Strontium picrate	$[C_6H_2(NO_2)_3O]_2Sr$	543.8	....	....	196.0	196.8
Sulphur dioxide	SO_2	64.1	69.3	75.3	....	77.9
Sulphuric acid	H_2SO_4	98.1	188.4	189.8	192.2	208.8
Sulphur trioxide	SO_3	80.1	91.5	101.1	103.2	139.0
Tetryl	$C_7H_5N(NO_2)_4$	287.1	....	....	−10.4	
Toluene (toluol)	$C_6H_5CH_3$	92.1	−9.0	0		
Triacetin	$C_3H_5(CH_3COO)_3$	218.2	....	307.3		
Trinitrobenzene (1 : 2 : 4)	$C_6H_3(NO_2)_3$	213.1	....	....	−5.4	
Trinitrobenzene (1 : 3 : 5)	$C_6H_3(NO_2)_3$	213.1	....	....	4.9	
Trinitronaphthalene (1 : 3 : 8)	$C_{10}H_5(NO_2)_3$	263.2	....	....	5.7	
Trinitrophenol	(Same as Picric Acid)					
Trinitrotoluene (2 : 4 : 6)	$C_6H_2(NO_2)_3CH_3$	227.1	....	....	16.5	
Urea	$CO(NH_2)_2$	60.1	....	....	79.1	77.2
Urea nitrate	$CO(NH_2)_2HNO_3$	123.1	....	....	136.8	126.0
Water	H_2O	18.0	57.81	68.38	69.7	
Wood meal (hardened) corresponding to	$C_{50}H_{72}O_{33}$	1201.1	....	....	1494.	
Zinc picrate	$[C_6H_2(NO_2)_3O]_2Zn$	521.6	....	....	102.8	114.3

Data for this Table furnished by Picatinny Arsenal.

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